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Individual differences in working memory capacity

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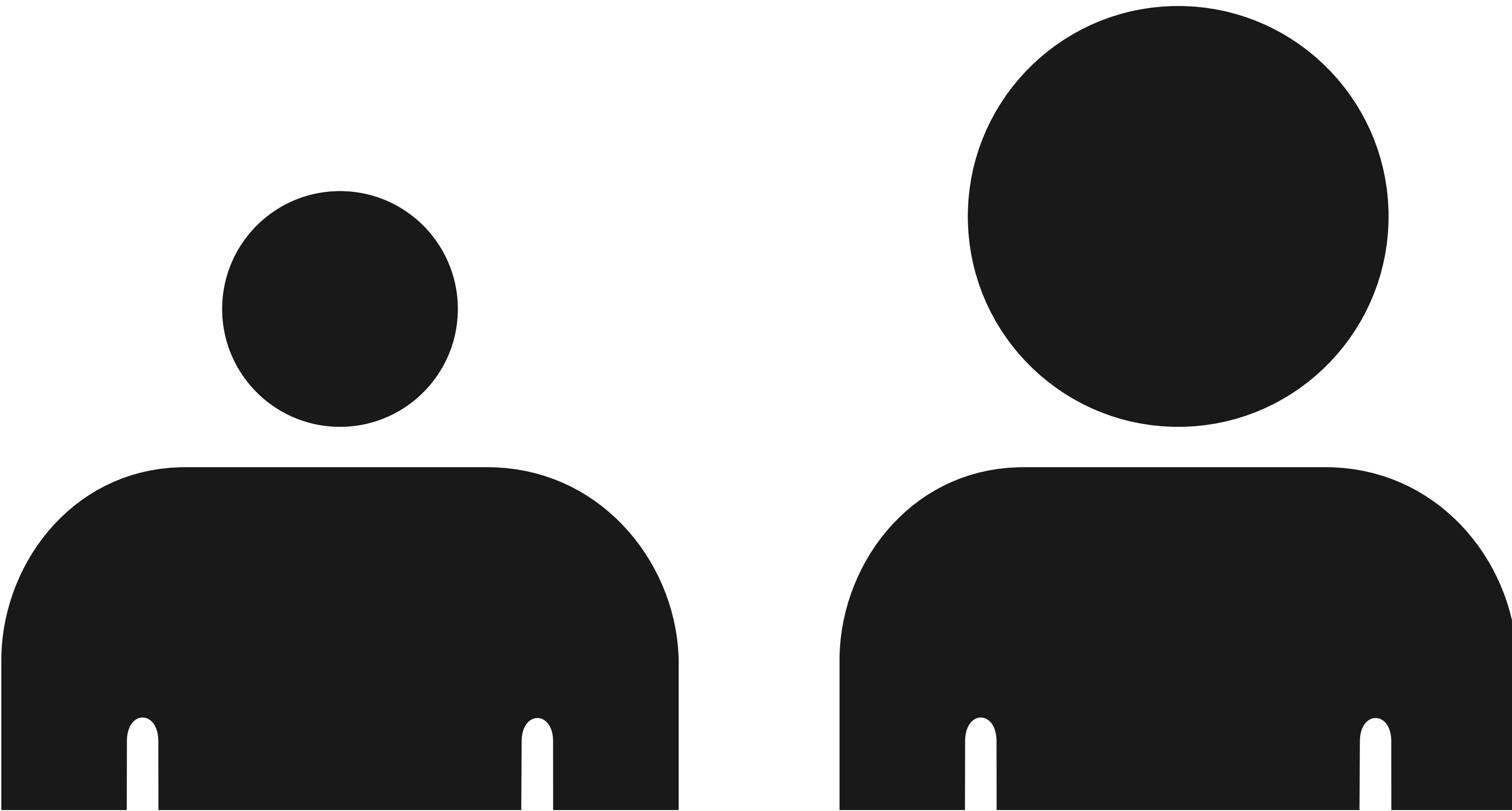
Individual Differences in Working Memory Capacity

Storage and Strategy

Jonathan Taddäus Mall



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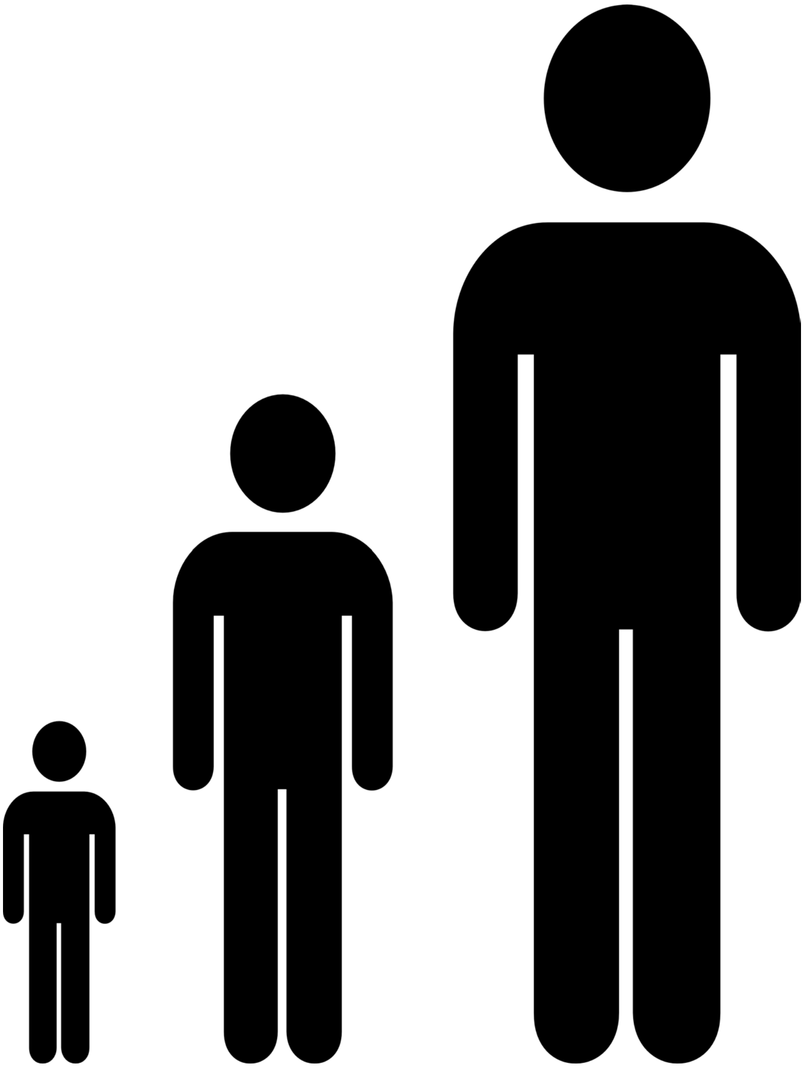


CHAPTER 1 INTRODUCTION

Working memory capacity (WMC), the ability to keep information in mind in the face of distraction, is an important pre-requisite for normal cognitive functioning and learning. Imagine holding your first lecture, you are trying to remember new names and explain what is on the slides while people come in late and others start chatting. Holding a good lecture in this scenario requires maintenance and processing of information while filtering out irrelevant stimuli. Since successful maintenance and concurrent processing are important factors in many everyday tasks, WMC measures are used extensively in clinical and educational settings. Nevertheless, there is much debate about the exact properties and limitations of the cognitive system underlying WMC. One of the most fruitful approaches trying to settle this debate is individual difference research.

Individual difference research, examining the natural variability of WMC and other cognitive abilities, can help to illuminate the structure of working memory (WM) and offers evidence towards explaining why individuals with high-WMC generally excel at higher-level cognitive tasks such as reading comprehension (Just & Carpenter, 1992) and fluid intelligence (Oberauer, Schulze, Wilhelm, & Süß, 2005; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). Individual difference studies often use latent variable analysis, a technique to identify variables that can't be directly observed. Latent variables represent shared variance between different measures which, depending on the selection of tasks, indicates the contribution of theoretically defined constructs. For example, performance on WMC tasks load on a factor which is dissociable from short term memory and intelligence measures (Engle, Tuholski, Laughlin, & Conway, 1999). Thus, WMC measures capture a unique ability that goes beyond simple span task performance such as remembering randomly created lists of digits or words (Turner & Engle, 1989). But how can WMC be measured most accurately?

The most common WMC measure in individual differences research is the complex span task. Daneman and Carpenter, (1980) and others have developed these tasks to measure the quality of WM in an individual by requiring serial recall of information that is maintained over a short period of time while a distracting processing task is interspersed. Thereby, these tasks tie up the ability to store and process information but they can differ widely in the type of information to be maintained; for example, letters, words, spatial location or orientation etc. and in the type of processing task; e.g. reading sentences, solving math problems, counting circles etc. (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Turner & Engle, 1989). As such, WMC tasks are a good reflection of the diversity of every day cognitive tasks wherein one must switch quickly between activities while remembering the results of intermediate steps. Likewise, scores on WMC tasks are generally found to be an excellent predictor of higher order cognitive abilities (Jarrold & Towse, 2006) and scholastic achievements (Alloway, 2009; Daneman & Carpenter, 1980). As the relationship between WMC and higher order cognitive abilities is generally not dependent on the domain of the to-be-remembered material (e.g., verbal or visuospatial memoranda) and is strongly related to central executive processes such as updating information or inhibiting natural responses, it may be interpreted as evidence for a domain-general WMC resource (Cowan, 2004). The question of whether WMC is best understood as a domain specific or domain-general resource has important practical and theoretical implications.

Theoretically, the interpretation of WM being a domain general resource is not fully compatible with one prominent view of working memory, Baddeley's multi-component model. In this model, two independent passive sub-systems hold information in separate stores (Baddeley, 2003). The visuo-spatial sketchpad holds visual information while the phonological loop holds verbal information. The contents of both stores can be sustained by active rehearsal to prevent forgetting due to temporal decay. The components are subordinate to a central executive which is controlling a range of executive functions such as sustaining attention, task switching, updating and inhibition (Baddeley, 2007).

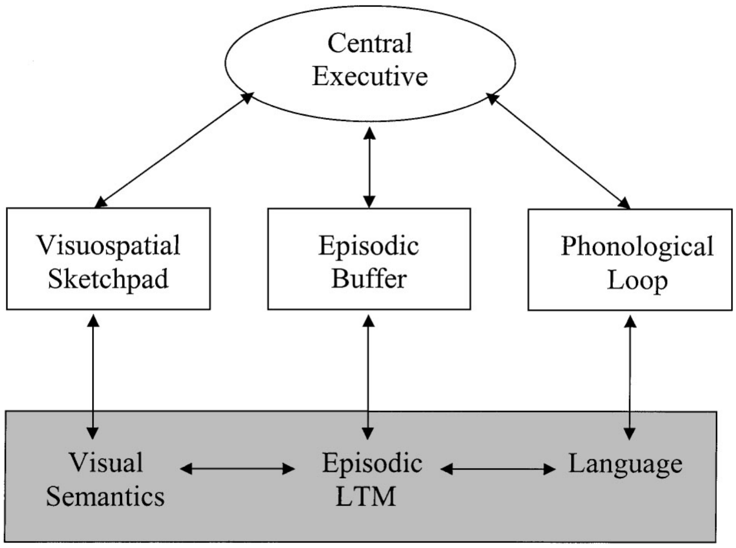


Figure 1. Baddeley's multi-component working memory model (Baddeley, 2000)

Evidence for the domain-specific nature of WM storage comes from studies that examine whether span task performance, using memoranda from different domains, loads on a different or a single factor (Shah & Miyake, 1996). Shah and Miyake (1996) presented participants with different complex span, simple span and visual and verbal aptitude tests.

They found two dissociable factors, spatial tasks loading on one and verbal tasks loading on another. Conversely, they found that reading span, a verbal task, exclusively predicted verbal scholastic Aptitude Test (SAT) scores while the spatial task predicted performance on a standardized visuospatial test. Although domain specific span tasks have been found to predict domain specific performance, i.e., a verbal span task predicting verbal abilities (Friedman & Miyake, 2004; Handley, Capon, Copp, & Harper, 2002) others found that working memory tasks also load on a domain-general factor (Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000). A follow up study by Oberauer, Süß, Wilhelm and Wittman (2003) re-examined evidence for dissociable storage components by administering a large number of tasks which were designed to measure specifically one processing or one content domain and complex span tasks with combinations of the processing and content components. Strong evidence was found for commonality between all working memory measures while evidence for a distinction between verbal and visuospatial storage was conspicuously weak. The only component in the Baddeley model which could account for domain-general resources is the episodic buffer, a slave system dedicated to combining information across domains, which was recently introduced to account for the multimodal interaction of subcomponents (Baddeley, 2000). However, shifting the emphasis away from the domain-specific nature of WM posits a challenge to Baddeley's theoretical assumptions, especially as other WM models, such as Cowan's embedded process model, focus on the domain-general nature of WM.

Cowan's embedded process model envisions a unitary structure of memory divided into three faculties. The faculties are: (1) Long term memory, (2) an activated portion of long term memory and (3) the focus of attention(Cowan, 1995; Oberauer, 2002, 2006). Similar to Baddeley's framework, there is a central executive that controls the focus of attention, dependent on incentives and task instruction. Additionally, the focus is guided by an involuntary attention orientating system influenced by salient events (e.g. loud noises or bright lights). The focus of attention is limited to about 4 items (Cowan, 2001; Luck & Vogel, 1997; Sperling, 1960) while activation is limited by time, with representations fading from memory when not actively rehearsed (Cowan, Lichty, & Grove, 1990; Cowan et al., 1994; Cowan, Saults, & Nugent, 1997).

Since Cowan's model lacks clear distinctions between different modalities, it overcomes the necessity to define the importance of domain specific codes in cognitive performance. As such, it fits individual difference research that supports a domain-general view of WMC (Oberauer et al., 2003). Strong evidence for this view has also been reported by Kane et al., (2004), who asked participants to do various short-term and working memory tasks that

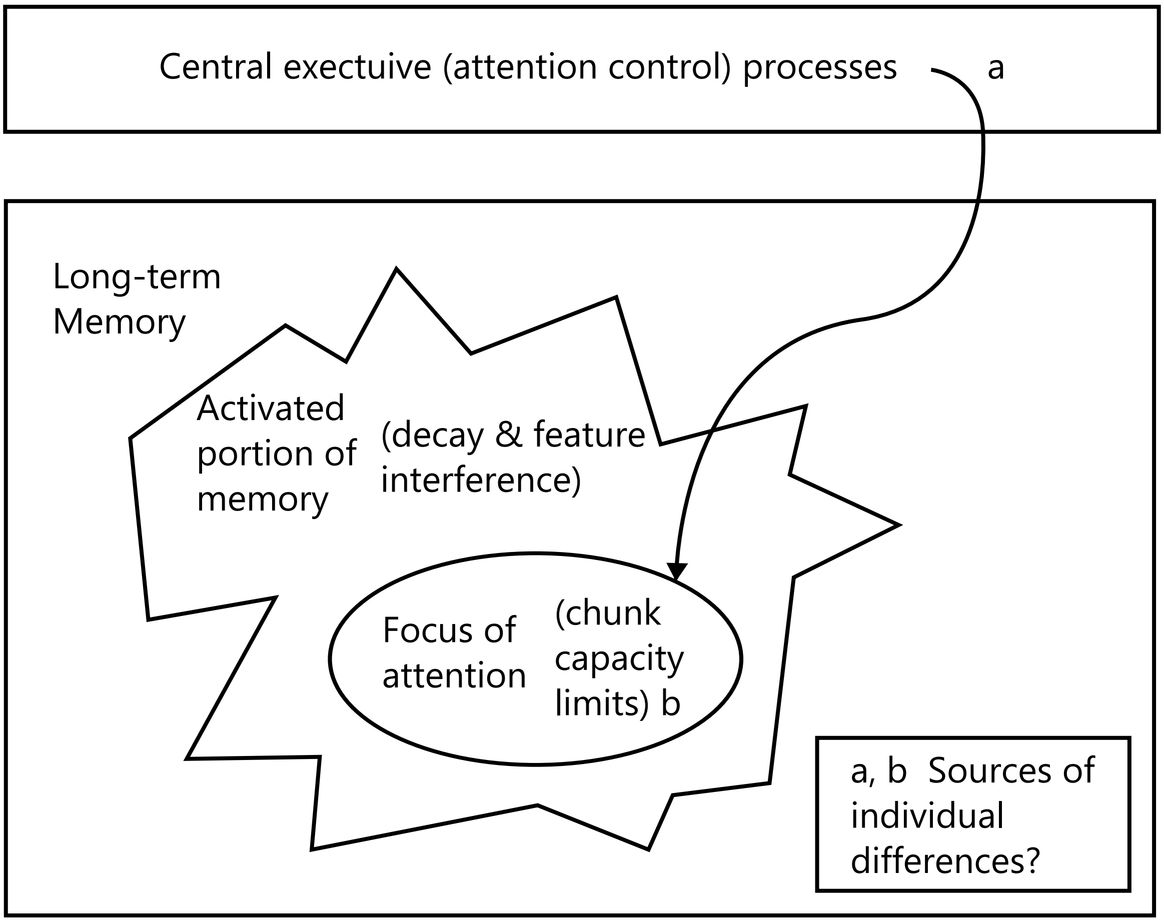


Figure 2. Cowan's memory model (Cowan, 1988)

required storage of verbal or visuospatial material. The best fitting model, obtained using confirmatory factor analysis, resulted in a unitary WMC factor irrespective of storage domain. Inferior models, that did include different factors for the verbal and spatial domain, had a strong correlation between the factors, which suggests that even if a domain-specific contribution of passive storage exists, WMC seemed to be mostly determined by a common and domain-general resource. Furthermore, Kane et al., (2004) argued that WMC reflects an attention control capability in which memory representations are maintained in an accessible state.

The second chapter of this thesis, in which interference between concurrent verbal and spatial information is examined, can be understood as a test for the discussed assumption that WMC reflects a domain-general resource. Treating WM as a domain general resource has the practical advantage that it allows for the closer examination of the general relationship between working memory and other cognitive abilities. These abilities include selective attention and efficient retrieval from long term-memory, which are the subject of chapters 3 and 4. While individual difference research has helped to outline the structure underlying WMC, it also aims to illuminate the relationship with cognitive abilities which may explain why individuals with high-WMC excel at higher-level cognitive tasks (Jarrold & Towse, 2006).

To explain the relationship between WMC and higher order cognitive abilities, two main types of theories have been developed over recent years. One type emphasizes individual differences in storage capacity (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Cowan et al., 2005) whereas the other emphasizes the aforementioned executive abilities (Engle et al., 1999; Kane et al., 2004; Kane, Conway, Hambrick, & Engle, 2007; Unsworth et al., 2009). These theories predict behavioural differences between individuals with high or low-WMC which can be illustrated using three key phenomena: Goal maintenance, selective attention and proactive interference.

The first possible source for the difference between low and high-WMC individuals is goal maintenance, the ability to keep the task relevant goal in an easily accessible state, especially in tasks that involve the inhibition of strong behavioral habits. A good illustration is the anti-saccade task. This task requires participants to move their eyes towards a visual stimulus by performing a pro-saccade or to look away from a flashing stimulus by performing an anti-saccade. Studies found that low-WMC individuals made more errors and were consistently slower to inhibit reflexive pro-saccades (Kane, Bleckley, Conway, & Engle, 2001; Unsworth et al., 2004). These findings can be explained by low-WMC individuals' inability to hold the task goal active and accessible, and hence falling back into the behavioral habit of reflexively directing attention to the most salient stimulus. Neglecting the task goal can be a product of more frequent attentional lapses which also seems more prevalent in low-WMC individuals as they report to have more frequent everyday cognitive failures, e.g. losing keys or forgetting the name of a newly introduced person (Brewer & Unsworth, 2012). Similarly, low-WMC individuals exhibit a bigger Stroop effect than high-WMC individuals when the majority of trials are congruent (Kane & Engle, 2003). This effect may be due to low-WMC individuals' goal neglect. In a context of mostly congruent trials, the correct response can usually be given regardless of whether the stated task goal, naming the ink color, is active. When a rare incongruent trial occurs, individuals with low-WMC then show marked slowing. Alternatively, a conflict-rich context may act as a reminder of the task goal and thereby help to overcome goal maintenance deficits (Hutchison, 2011; Kane & Engle, 2003; McVay & Kane, 2009; Morey et al., 2012). However, manipulating task context alone is not sufficient to produce the predicted relationship between conflict resolution and WMC. Morey et al. (2012) found no WMC differences in cross-modal versions of the Stroop task, which involve Stroop-like semantic conflicts but no conflict between color-naming and reading. This suggests that temporarily forgetting the task goal and not resolving the interference between task-relevant and task-irrelevant information underlies the relationship between WMC and the Stroop effect. Possible goal neglect effects were additionally illustrated when an auditory monitoring task was added to the cross modal Stroop task, requiring participants to listen for rare tones in the auditory stream. Under such attentionally demanding circumstances, low-WMC individuals made more errors in the monitoring task than their high-WMC counterparts. While this could suggest that WMC indexes executive functions, such as the ability to actively maintain the task goal or the propensity of attentional lapses, capacity differences may also play a role.

Performance in tasks requiring goal maintenance might, at least partly, depend on the capacity to actively maintain task instructions and the appropriate stimulus-response mappings. If no capacity is available to hold the task goal accessible and the task context can't aid its retrieval, low capacity individuals would be at a disadvantage compared to individuals who are able to hold more information accessible including all task relevant representations (Chuderski et al., 2012). Likewise, resilience against salient distractions could be modulated by storage differences. For example, in a reanalysis of an anti-saccade task, Chuderski et al., (2012) compared individuals with a big or small scope of attention (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006) and found that only individuals with the capacity to hold on to less than two pieces of information made more errors compared to individuals whose capacity was bigger. Holding on to the instruction to look away from the salient stimulus was only difficult for those whose limited scope may have been easily replaced by a distractor. Chuderski et al., (2012) further argued that distracting information may not replace all task relevant information simultaneously but slowly crowd out the relevant information which would be less costly for individuals who have more capacity to compensate. Thus, successful goal maintenance could either be indexed by WMC because of efficient attentional control or be due to an excess of capacity. Nevertheless, tasks that require selective attention, an ability that is arguably more reliant on attentional abilities, show strong correlations with WMC.

A good illustration of the relationship between selective attention and WMC is the cocktail party effect, a phenomenon in which the own name is noticed in a nearby conversation while one is engaged in a different conversation at a cocktail party. Reproducing this phenomenon in the laboratory, Conway, Cowan and Bunting (2001) had participants perform a dichotic listening task in which different streams of words were presented to each ear and the relevant stream had to be repeated aloud. Low-WMC individuals noticed their own name, which was occasionally presented in the irrelevant stream, much more frequently than high-WMC individuals, indicating a deficit to selectively attend to the relevant stream (Conway et al., 2001). When participants were asked instead to divide their attention between two streams and report immediately when they noticed their own name, high-WMC individuals reported hearing their own name more often than low-WMC individuals. This suggested that high-WMC individuals were able to both focus attention to the exclusion of irrelevant information or to divide attention between two relevant sources (Colflesh & Conway, 2007). Thus, depending on the situation, high-WMC individuals seemed able to flexibly control their attention.

However, the relationship between WMC and selective attention towards auditory information appears to be more nuanced. For instance, irrelevant speech effects, the decline in performance when listening to irrelevant auditory stimuli during a memory task, was found to be weakly associated with WMC (Elliott & Cowan, 2005) or not associated at all (Beaman, 2004). Only when irrelevant speech was semantically related to the to-be-remembered items did low-WMC individuals perform worse than high-WMC individuals (Beaman, 2004). In general, WMC has been exclusively found to strongly correlate with the deteriorating effect of unexpected, infrequent auditory distractors but not continuous and predictable distraction (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2012; Sörqvist, 2010). While some evidence suggests that the same boundary conditions also limit visual selective attention (Fukuda & Vogel, 2009), clear boundary conditions for visual selective attention have yet to be formulated.

For visual information on the other hand, it seems at first glance that high-WMC is directly associated with effective selective attention towards relevant visual information. Vogel, McCollough, and Machizawa, (2005) used a visual change detection paradigm featuring relevant and irrelevant items and a neural measure which indicated how many items were maintained over a short period of time. When both relevant and irrelevant item were displayed, low-WMC individuals exhibited an event-related neural pattern that tracked the total number of items displayed whereas high-WMC individuals' neural pattern seemed to track only the number of relevant items. Vogel et al. (2005) argued that participants with low-WMC inadvertently stored irrelevant items whereas participants with high memory performance stored only the relevant information. Since successful filtering has been found to be associated with brain activity in the basal ganglia, this attentional filtering view has been likened to high-WMC having a more efficient bouncer in the brain who only lets the "relevant" people into the nightclub (Awh & Vogel, 2008).

The evidence from selective visual attention studies does not fit with the evidence from selective auditory attention studies, in which low-WMC individuals were merely more susceptible to involuntary attentional capture (Hughes et al., 2012; Sörqvist, 2010). Studies investigating the relationship between selective visual attention and WMC (e.g. Fukuda & Vogel, 2009; McNab & Klingberg, 2008; Vogel, McCollough, & Machizawa, 2005) are furthermore limited in their interpretability by relying on the visual task itself to estimate WMC. By using visual short term memory performance and not complex span tasks to estimate WMC, the described relationships may be driven by processes such as WM storage capacity rather than the attentional control ability described in the individual difference literature. In fact, young children, who are known to have low-WMC, demonstrated an intact ability to ignore irrelevant information when their storage capacity was not exceeded (Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010). As WMC increases with age, it may be additional storage capacity, not better attentional control, which enables adult high-WMC individuals to excel in visual change detection tasks (Shipstead & Engle, 2013). Therefore, the third chapter of this thesis describes an attempt to reconcile the described selective attention literature and to evaluate the contribution of attentional control and storage.

Finally, the susceptibility to proactive interference is closely related to WMC. Because short-term memory capacity is limited to three to four objects (Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997; Sperling, 1960), remembering any irrelevant information significantly impacts performance. Consider operation span (Unsworth, Redick, Heitz, Broadway, & Engle, 2009), where participants are asked to remember series of up to seven letters while solving intermittent mathematical equations. Recall of the current set's letters becomes increasingly difficult as knowledge about previous letters builds up over successive trials as proactive interference. Resistance to proactive interference may therefore help to obtain high-WMC scores. If resolving such interference is an important factor in WMC differences and its relationship with other cognitive abilities, removing proactive interference from the WMC task should remove that relationship. Thus, when Lustig, May and Hasher (2001) reduced the amount of interference in a WMC task, WMC scores improved, but it removed an otherwise positive correlations between WMC and prose recall. This and similar findings (Bunting, 2006) suggest that resistance to proactive interference plays a crucial role in the relationship between WMC and higher order cognitive tasks.

A possible explanation for the observed resilience to proactive interference by high-WMC individuals is given by Unsworth and Engle (Unsworth & Engle, 2007a, 2007b) who argue that high-WMC individuals use more specific retrieval cues during memory search. Using specific retrieval cues delimits the search set to relevant items whereas using unspecific cues allows irrelevant information to interfere. Unsworth and Engle (Unsworth & Engle, 2007a, 2007b)

found evidence in cued recall tasks where low-WMC individuals recalled fewer items, made more errors, and had longer recall latencies than high-WMC individuals (Unsworth, 2009). Such patterns suggest that the low-WMC individuals' search set was bigger and hence took longer to serach through. Interestingly, when Unsworth and Engle (2007) gave specific retrieval cues to guide retrieval, both high and low-WMC individuals benefitted to the same extent but high-WMC individuals still recalled more information. Even though Unsworth and Engle (2007) interpret this finding to indicate that low-WMC individuals committed more degraded representations to memory, one could also argue that when delimiting the search set was explicitly encouraged, high-WMC individuals still possessed bigger storage capacity, leading to better recall performance.

To test the hypothesis that high-WMC individuals use more specific retrieval cues to delimit their search set, the retrieval induced forgetting paradigm can be used (Anderson, Bjork, & Bjork, 1994). Retrieval-induced forgetting is believed to occur when competing memory traces are inhibited to allow for accurate retrieval. Only when items are part of the search set would they need to be inhibited, hence only individuals unable to delimit their search set should show retrieval-induced forgetting effects. Accordingly, when items share retrieval cues, only low-WMC individuals should exhibit significant retrieval-induced forgetting effects. In chapter 4, we used the retrieval practice paradigm to examine retrieval from long term memory and its interaction with individual differences in WMC.

In short, the discussed literature illustrates that WMC is a multifaceted phenomenon which is an important pre-requisite for normal and exceptional cognitive functioning. The main aim of this dissertation is to better understand the nature of WMC and to evaluate the importance of attentional control and storage capacity. To do so, this thesis contains two published (Chapter 2 & 4) and one submitted paper (Chapter 3) discussing a number of experiments using large samples of healthy university students.

1.1 Dissertation Outline

1.1.1 Chapter 2

In the paper "Cross-domain interference costs during concurrent verbal and spatial serial memory tasks are asymmetric" the extent to which working memory relies on domain-general or domain-specific sub-systems is explored. We first examined single-and dual-task performance in cross domain serial reconstruction tasks. By eliminating the effect of semantic integration and short-term sensory representations, we were able to describe the nature of resources supporting short-term storage.

1.1.2 Chapter 3

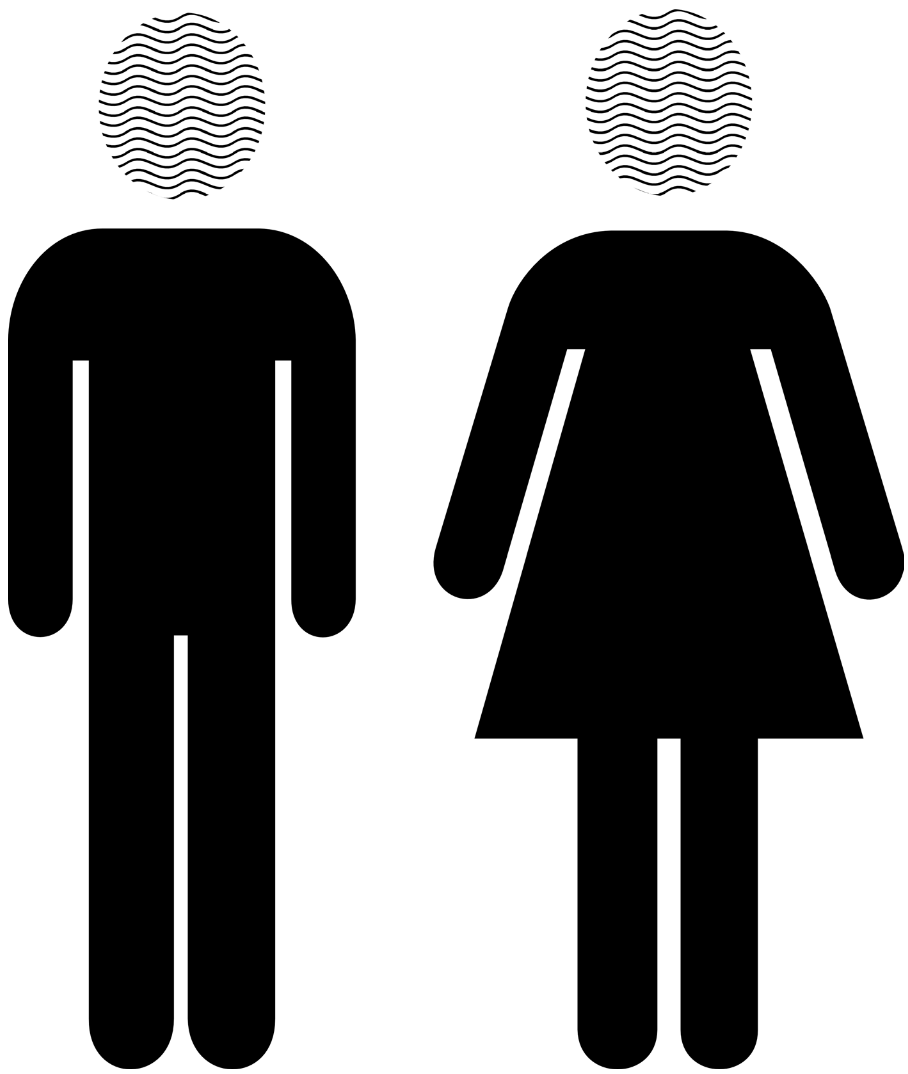
In the paper "Working memory capacity is more than just attentional control: Evidence from eye-movements during a visual working memory task" we examined the viability of a recent interpretation of working memory capacity as a virtual measure of filtering efficiency. Analysis of behavior and eye movements during a visual change detection task with different degrees of attentional filtering and allocation requirements allowed us to test whether people with low-WMC involuntarily encoded irrelevant information. By introducing a strong incentive to filter less relevant information, individual differences in the strategic allocation of attentional resources became evident.

1.1.3 Chapter 4

In the paper "High working memory capacity predicts less retrieval induced forgetting" the relationship between WMC and retrieval from long term memory was explored. The retrieval-induced forgetting paradigm was used to compare the effect of using appropriate retrieval cues to guide memory search. By manipulating the amount of interference between different study materials, we found a relationship between WMC and retrieval-induced effects under specific interference conditions.

1.1.4 Chapter 5

This chapter aims to integrate the results presented in this dissertation. The discussion will focus on the following two questions (1) What are the implications for future research? (2) What practical lessons can be learned?



CHAPTER 2 DOMAIN GENERALITY

A version of this chapter has been published as Morey, C. C., & Mall, J. T. (2012). Cross-domain interference costs during concurrent verbal and spatial serial memory tasks are asymmetric. The Quarterly Journal of Experimental Psychology, 65(9), 1777-1797 and can be accessed online http://www.ncbi.nlm.nih.gov/pubmed/22512308

2.1 Abstract

Some evidence suggests that memory for serial order is domain-general. Evidence also points to asymmetries in interference between verbal and visual-spatial tasks. We confirm that concurrently remembering verbal and spatial serial lists provokes substantial interference compared with remembering a single list, but further investigate the impact of this interference throughout the serial position curve, where asymmetries are indeed apparent. A concurrent verbal order memory task affects spatial memory performance throughout the serial positions of the list, but performing a spatial order task affects memory for the verbal serial list only for early list items; in the verbal task only, the final items are unaffected by a concurrent task. Adding suffixes eliminates this asymmetry, resulting in impairment throughout the list for both tasks. These results suggest that domain-general working memory resources may be supplemented with resources specific to the verbal domain, but perhaps not with equivalent spatial resources.

2.2 Introduction

Although many investigators have compared performance on serial verbal and spatial memory tasks with the aim of determining whether they rely on separate or predominantly shared memory resources, inconsistencies in results prevent a clear consensus from emerging. Similar studies have yielded results varying from equal interference to spatial or verbal memory tasks from verbal and manual suppression (Jones, Farrand, Stuart, & Morris, 1995), contradicting Baddeley's (1986) multi-component model of working memory, to convincing evidence of selective interference between domain-specific memory and rehearsal suppression tasks (Logie, Zucco, & Baddeley, 1990), at least under certain conditions (Farmer, Berman, & Fletcher, 1986; Meiser & Klauer, 1999). These disparities stoke controversy about the structure of a working memory system: to what extent are domain-general and domain-specific resources involved in serial memory?

Baddeley's prominent multi-component model of working memory (1986; 2007) proposes independent stores able to hold and rehearse information from different domains in parallel. The multi-component model of working memory was inspired by the work of Baddeley and Hitch (1974), particularly their finding that maintaining a small verbal memory load induced little or no detrimental effect on a concurrent verbal reasoning task. The finding that tasks requiring different mental operations could be performed simultaneously suggested some independence between mechanisms needed for these different mental operations, leading to a modular system including domain-specific storage buffers specializing respectively in verbal or visual-spatial maintenance. Proponents of modular models such as Baddeley's vary in the degree of domain-specific separation supposed. Whereas Baddeley envisions a domain-general executive system (1986), others have claimed separate attention systems for verbal and visual-spatial information (Shah & Miyake, 1996; Wickens, 2002).

In Baddeley's modular system, it is assumed that activities of one storage buffer should not affect activities of another, but this very strict interpretation does not withstand scrutiny. Jones, Farrand, Stuart and Morris (1995) measured serial verbal and spatial recall during concurrent tasks designed to selectively limit verbal or spatial rehearsal capabilities. However, they did not observe selective interference. Instead, they observed that articulatory suppression (repeating aloud a previously learned verbal sequence) impaired memory for sequences of spatial locations as much as it impaired memory for sequences of words. Similarly, repeatedly tapping a series of keys impaired memory for spatial locations and words to an almost equal degree. However, studies of interference with serial memory from rehearsal suppression do not consistently show such strong evidence of domain-general interference (for example, Farmer, Berman, & Fletcher, 1986; Guérard & Tremblay, 2008). In a particularly relevant study, Meiser and Klauer (1999) attempted to replicate the findings of Jones et al., and in addition, compared the impact of rehearsal suppression separately during encoding and retention of sequences of words and spatial locations. Meiser and Klauer observed domain-specific selective interference when articulatory suppression or spatial tapping was carried out during encoding of the to-be-remembered word or location sequences. However, when rehearsal suppression was carried out during retention, a more complex pattern of interference emerged: both articulatory suppression and spatial tapping interfered with spatial sequence memory (indicated by a significant main effect of performing a secondary task, but no effect of the modality of the secondary task), while articulation interfered selectively with verbal sequence memory. Meiser and Klauer argued in favor of a modular system like Baddeley's multi-component model, but their data are not necessarily consistent with a model that proposes separate domain-specific storage buffers with equivalent capabilities. This pattern could also be interpreted as evidence that spatial sequence memory is sensitive to interference from a variety of sources, and perhaps more vulnerable to domain-general interference than verbal sequence memory.

The studies of Jones et al. (1995) and Meiser and Klauer (1999) examined memory for verbal or spatial materials during rehearsal suppression tasks. What if a concurrent task also requires storage? Interference between the maintenance of two cross-domain stimulus sets does not seem to be negligible. Saults and Cowan (2007) estimated working memory capacity for visual arrays of colored shapes and auditory arrays of several voices speaking at once, and compared estimates of capacity when these tasks were carried out separately or simultaneously. In a subset of their experiments in which sensory masks were employed (presumably eliminating sensory memory traces from which information may be extracted), Saults and Cowan observed summed dual-task capacities equal to single-task capacity, consistent with the possibility that visual-spatial and auditory-verbal materials compete for a common store. Cowan and Morey (2007) also found evidence that storage capacity is constant regardless of stimulus domain. They presented two sets of stimuli, which could be two verbal lists, two visual arrays, or one verbal list and one visual array, and in some conditions, cued participants quickly after the stimulus presentation, letting them know which stimulus set would be tested after the retention interval. When the retro-cue warned participants which stimulus set would be tested, participants could then selectively rehearse or refresh this information throughout the retention interval. Cowan and Morey compared uncued conditions, in which some items from both stimulus sets were presumably remembered with retro-cued conditions in which participants could focus their efforts exclusively on the to-be-tested stimulus set, and found similar costs of maintaining two stimulus sets regardless of whether the sets contained stimuli from the same or different domains. However, Cowan and Morey did observe greater interference between two sets from the same domain than two sets from different domains, reflected in the cost between trials with only one to-be-remembered stimulus set and retro-cued trials with two stimulus sets, which suggests that encoding two stimulus sets of the same domain incurred a steeper cost than encoding stimulus sets from different domains. Together, this evidence suggests that storage operations involved in working memory maintenance may not be domain-specific (at least not when information must be preserved for more than a second or so), but that operations involved in encoding cross-modal sets of information could be more independent. These findings are consistent with the proposal of brief domain-specific memory representations, but further suggest that this information must be quickly consolidated into a domain-general resource.

Memory for serial lists, which requires the maintenance of some stimuli during the presentation of subsequent stimuli over time, may also be sensitive to interference from a concurrent memory task, even if the to-be-remembered stimuli come from distinct domains or modalities. Even if brief domain-specific memory representations are available, as Cowan and Morey's (2007) data suggest, these representations might not be robust enough to withstand interference from consolidating subsequent list items or frequently switching attention to subsequent items, regardless of the domain of the presented information. Depoorter and Vandierendonck (2009) created memory tasks which required retention of item identities or sequential order, and combined them in an experimental design in which either an item and an order task, two item tasks, or two order tasks were performed concurrently. Regardless of the domain of the items in each stimulus set, when both tasks required order memory, interference was observed, whereas little or no interference was observed when remembering two sets of items simultaneously. However, Depoorter and Vandierendonck's results in their concurrent order task conditions seem to confirm the asymmetric pattern we discerned in Meiser and Klauer's (1999) data, in that somewhat more interference was found when the verbal order memory task was embedded within the spatial order memory task (dual-task performance is 76% of single-task performance) than when the spatial order task is embedded within the verbal order task (dual-task performance is 88% of single-task performance). This pattern, in which auditory-verbal tasks seem to interfere more with visual-spatial tasks than visual-spatial tasks interfere with auditory-verbal ones (see also Morey, Cowan, Morey, & Rouder, 2011; Shah & Miyake, 1996) seems persistent and is logically consistent with propositions that spatial memory is more closely related to attention (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) or perhaps requires more attentional support than verbal memory (Gmeindl, Walsh, & Courtney, 2011), or has access to fewer resources for rehearsal than verbal memory (Camos, Lagner, & Barrouillet, 2009). Though the possibility of incorporating these assumptions into models of working memory has been acknowledged (Barrouillet & Camos, 2010), the implications of these assumptions have not been thoroughly explored.

Serial position information would yield useful information about potential sources of this asymmetry, but Depoorter and Vandierendonck (2009) required all-or-none recognition or rejection of test sequences, yielding no way to compare interference effects throughout the serial position curve. We therefore lack detailed information on what precisely is forgotten when two lists are concurrently maintained. This information could be essential for reconciling disparities presented by previous research. Across a serial list, early items must be maintained while subsequent items are encoded. We suppose that encoding verbal and spatial materials can be accomplished with minimal interference (Cowan & Morey, 2007), but that a common resource may be necessary for maintenance of both verbal and spatial serial order (Depoorter & Vandierendonck, 2009). This resource may also be supplemented by domain-specific storage buffers or sensory memory stores, which should not be sensitive to cross-domain interference (Baddeley, 2007). Assuming these stores temporarily maintain incoming information, we suppose that they should maintain the most recently presented stimuli. Is there any cross-domain cost for these items? If so, does it occur to both verbal and spatial representations?

We first aim to confirm that interference between two order memory tasks occurs, and then to examine whether this dual-maintenance cost occurs for early-list items, for late items, or both. We approached this problem by comparing single- and dual-task performance on serial reconstruction tasks (Guérard & Tremblay, 2008), which we chose in order to equate the demand of the two tasks as far as possible and because previous research on order memory suggested that two cross-domain order memory tasks would interfere with each other (Depoorter & Vandierendonck, 2009). In this procedure, lists of stimuli were presented and then at test, all items re-appeared onscreen. Participants' task was to indicate the order in which the stimuli were presented. In our version of these tasks, words were presented aurally and spatial locations (represented by squares) were presented at unpredictable locations randomly selected from a large area on the screen in order to reduce any strategic attempt to verbally label the spatial locations. We constructed the tasks so as to make the to-be-remembered stimuli as similar as possible in all respects except for their domain, as we wanted to measure interference between two stimulus sets encoded by different perceptual systems.

We compared reconstruction performance when only a single list was presented with reconstruction performance when verbal and spatial lists were presented in an interleaved fashion. Sometimes, participants were unaware of which of the two interleaved lists would be tested; in these cases, they should have attempted to maintain both lists simultaneously. In order to control for the processes involved in perceiving the interleaved stimuli and to ensure that we could attribute any interference we observed in the uncued dual-presentation condition to processes involved in maintenance, participants were sometimes cued prior to stimulus presentation so that they knew which list would be tested. In this design, observing no interference in the uncued, dual-maintenance condition would be strong evidence for a model of working memory positing separate resources for verbal and visual-spatial information, as suggested by Shah and Miyake (1996). However, if interference in the dual-maintenance condition were found, its locus in the serial position function will help us better understand the nature of the interference. Cross-domain interference early in the list would be consistent with the proposal that maintaining or consolidating incoming items from a list in serial order requires domain-general resources; a lack of interference for items from end of the list would be consistent with the proposal that incoming information is at least briefly segregated into domain-specific stores. Analysis of correlations between the verbal and spatial tasks will also be examined, providing additional information for theorizing about which mental resources are shared by these tasks, and which are separate.

2.3 Experiment 1

2.3.1 Method

2.3.1.1 Participants

Sixty-four students from the University of Groningen (42 women, 22 men, age ranged 18-29 years, M = 20.89 years, SD = 1.67) participated as part of their course requirements. All participants in this and subsequent experiments were fluent English-speakers, following a university curriculum taught entirely in English.

2.3.1.2 Apparatus, Stimuli, and Design

The stimuli were controlled using E-Prime 2.0 (Schneider, Eschmann, & Zuccolotto, 2002), with a screen resolution of 1024 x 768 pixels. All visually displayed objects were black on a white background. The verbal stimuli were 36 English one-syllable concrete nouns selected using the English Lexicon Project (Balota et al., 2007) for moderate frequency ranging from 8030 and 11722 per million (M = 9662) according to the HAL study frequency norms frequency based on HAL corpus (Lund & Burgess, 1996). A native female English speaker recorded the words. The sound files were recorded at 16 bits per sample and 22050 Hz, and normalized. Articulation times ranged from 452 to 799 ms (M = 610). Sounds were presented via stereo headphones in a single channel using the onboard sound card. Word sequences were randomly selected without replacement from the 36-word list at the beginning of each trial. Words used in each of our experiments are given in the Appendix.

The spatial stimuli were black squares of 75 x 75 pixels (1.98 cm), presented at different locations in a 500 x 500 pixel (13.23 x 13.23 cm) window in the middle of a the screen. Locations were determined randomly at the beginning of each trial with the constraint that no two squares could be closer than 35 pixels (0.93 cm) to each other.

Our design included three repeated-measures factors: three different presentation conditions (single, cued, and uncued), two task domains (verbal and spatial), and three list lengths (3, 5, and 7). In the single presentation condition, either a verbal or a spatial list was presented and tested, with inter-stimulus timings equal to those in the dual-presentation conditions. In the cued and uncued presentation conditions, the verbal and spatial lists were presented in an interleaved fashion, always with an equal number of items in each list. In the cued presentation condition, participants saw a cue that read either "word" or "location" prior to stimulus presentation, which always accurately indicated which list would be tested. In the uncued condition, participants saw a "?" instead of an informative cue, and therefore should have tried to maintain both lists until the test screen appeared. The cued condition was included as a fairer control for dual-maintenance comparison than the single presentation condition; stimulus presentation was identical to that in the uncued condition, with the only difference being that participants knew in advance which list would be tested in the cued condition. We included short lists, for which serial position data could not be very informative, in order to ascertain whether any dual-task costs we observed occur for sub-span as well as supra-span lists. Stimulus presentation order (i.e., whether interleaved stimulus presentation began with a word, then a square, then another word, etc., or began with a square, then a word, then another square, etc.), varied between participants with approximately equal numbers taking part in the word-square order (N = 34) and the square-word order (N = 30). The order of the within-participants conditions was randomized.

2.3.1.3 Procedure

A depiction of a cued trial is given in Figure 1. All trials began with presentation of a fixation cross for a total of 2 seconds followed by the stimulus sequence. In both the cued and the uncued conditions, the first item (spoken word or square) was presented and the next item (square or spoken word) was presented 1 second after the onset of the first item. In both these conditions, the interleaving of an equal number of verbal and spatial items was repeated until the end of each list. For the single-presentation conditions, the stimulus timing was kept the same as for one of the interleaved lists in the dual-presentation conditions. Thus, in the single-presentation condition, the 1-second delay between offset of one item and the onset of the next item was unfilled, whereas in both dual-presentation conditions, presentation of the other stimulus occurred during this period. Cued and uncued dual-presentation conditions differed in what must be done with the intervening item; in the uncued condition, the intervening item should be encoded for possible later recall, whereas in the cued condition, the intervening item should be ignored.

One second after the offset of the last item, the serial reconstruction test screen appeared showing either all words, printed in a randomly-ordered vertical list in the middle of the screen with 25 pixels (0.66 cm) in between each word, or all squares at their original locations. Using the mouse, participants clicked the items in order until all words or squares were chosen. Clicking on an item marked it in green, so that the participant always knew which options had been selected. No omissions were allowed. Each trial ended with instructions to press the space bar to continue to the next trial. Participants completed 12 practice trials with feedback before the experiment began, to ensure that they understood the instructions, and then 90 experimental trials (5 for each combination of within-participant factors). The whole experimental session lasted approximately 50 minutes.

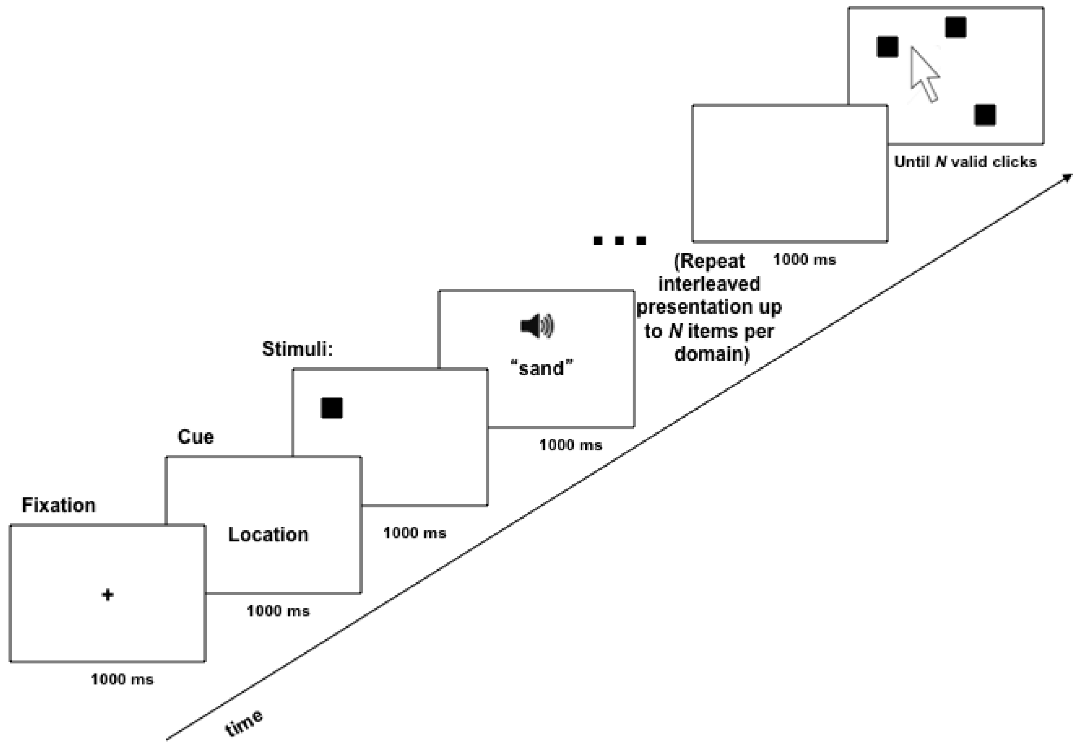


Figure 1. Depiction of trial events, Experiment 1. In this example, a cued 3-item location trial is shown. Locations or words could be cued for recall with equal probability. In the uncued presentation condition, a question mark appeared in place of a cue word. Stimulus presentation could begin with presentation of a word or presentation of a square, and alternated thereafter. N equals the number of items per list, and was always equal for each stimulus domain. In single-presentation trials, the periods occupied by the other stimulus presentation in dual-presentation trials were unfilled pauses. Depiction is not to scale.

2.3.2 Results

Our threshold for declaring statistical significance was always $p < .05$. In any case in which the sphericity assumption of the analysis of variance (ANOVA) was violated, the Greenhouse-Geisser correction was applied.

2.3.2.1 Whole List Accuracy

With mean number of correct responses per trial as the dependent variable, we conducted separate ANOVAs for each task domain, each with presentation condition (single, cued, uncued) and list length (3, 5, 7) as within-participant factors and stimulus presentation order as a between-subjects factor. Descriptive statistics for each of these combinations of variables are given in Table 1.

For the verbal task, we uncovered main effects of both presentation condition ($F(2,124)=42.50$, $MSE=.33$, $\eta 2p\ =.41$, $p<.001$) and list length ($F(2,124)=162.16$, $MSE=.85$, $\eta 2p\ =.72$, $p<.001$), which must be considered in light of significant interactions between presentation condition and order ($F(2,124)=3.42$, $MSE=.33$, $\eta 2p\ =.05$, $p<.05$), and all three factors ($F(4,248)=3.73$, $MSE=.47$, $\eta 2p\ =.06$, $p<.02$).

To understand this higher order relationship, we carried out separate ANOVAs with presentation condition and order as factors for each list length. For 7-item lists, a significant main effect of presentation condition ($F(2,124)=26.88$, $MSE=.74$, $\eta 2p\ =.30$, $p<.001$) was qualified by an interaction between presentation condition and order ($F(2,124)=4.84$, $MSE=.74$, $\eta 2p\ =.07$, $p<.02$). Bonferroni-corrected post-hoc comparisons indicate that for both orders, recall in the uncued condition (refer to means in Table 1) was worse (ps $<.02$) than in single-task or cued conditions, which did not significantly differ in either comparison (ps from .07-.87). The difference between the cued and uncued conditions was larger in the word-square order ($p<.05$). For 5-item lists, there was a main effect of presentation condition ($F(2,124)=16.06$, $MSE=.23$, $\eta 2p\ =.21$, $p<.001$) characterized by the same pattern as in 7-item lists, but no effect of order ($p>.59$) and no presentation condition by order interaction ($p>.67$). For 3-item lists, no significant effects or interactions were observed (ps from .52-.94). Thus, for the verbal reconstruction task, we observed a dual-task cost in the uncued condition for 5- and 7-item lists, and in 7-item lists, this cost increased for the participants who heard the word before seeing the location during interleaved presentation. For the 3-item lists, verbal reconstruction performance was always near ceiling, and no effects on it were observed.

For the same analysis in the spatial task, main effects of presentation condition ($F(2,124)=43.33$, $MSE=.48$, $\eta 2p\ =.41$, $p<.001$) and list length ($F(2,124)=86.35$, $MSE=1.22$, $\eta 2p\ =.58$, $p<.001$) were qualified by a significant interaction between these factors. No other effects or interactions reached criteria for statistical significance (ps from .06-.74). For the sake of comparison, we performed the same follow-up analyses on spatial task data as we performed on the verbal task data. For 7-, 5-, and 3-item lists, the effect of presentation condition was always statistically significant ($\eta 2p$ s from .06-.35, ps $<.03$). For 5- and 7-item lists, reconstruction in the uncued condition was lower (ps $<.003$) than in the cued or single-task conditions, which did not significantly differ (ps $>.83$; see Table 1 for means). For 3-item lists, reconstruction in the uncued condition was lower than in the cued condition ($p<.02$), while the other comparisons were not statistically significant (ps $>.19$). Neither the effect of order nor its interaction with presentation condition ever reached the criterion for statistical significance (ps from .06-.81).

	Spatial Task			Verbal Task		
	3	5	7	3	5	7
Word-Square Order ($N=34$)						
Single	2.92(.26)	4.31(.70)	4.82(1.15)	2.97(.12)	4.39(.54)	4.54(.94)
Cued	2.94(.21)	4.29(.78)	4.42(1.44)	2.97(.15)	4.32(.48)	4.36(.96)
Uncued	2.76(.35)	3.94(.90)	3.51(1.09)	2.94(.17)	3.97(.65)	3.19(1.13)
Square-Word Order ($N=30$)						
Single	2.87(.36)	4.11(.84)	4.11(1.48)	2.95(.17)	4.40(.58)	4.57(1.08)
Cued	2.90(.22)	3.95(.97)	4.15(1.31)	2.93(.18)	4.46(.50)	4.16(1.12)
Uncued	2.82(.30)	3.45(1.10)	2.99(1.26)	2.97(.13)	3.99(.70)	3.86(.87)

Table 1: Experiment 1 accuracy, by task domain, presentation condition, and list length.
Note. Mean number correct per list (with standard deviations).

Comparing verbal with spatial reconstruction performance, the verbal task seems more sensitive to stimulus presentation order than the spatial task and the spatial task perhaps more sensitive to cross-domain interference than the verbal task, because uncued performance was significantly impaired even for the shortest lists. While we observed some differences between the effects of list length, presentation condition, and stimulus order on verbal and spatial reconstruction, generally the patterns we observed were quite similar. Importantly, for both tasks cross-domain interference was observed for the longest list lengths, enabling us to analyze interference patterns across the serial position function.

2.3.2.2 Accuracy by Serial Position

We analyzed serial position only in the 7-item lists, which afford richer data for this analysis than shorter lists because accuracy is sufficiently far from ceiling. We compared the proportion of correct responses for each serial position in the 7-item lists and analyzed the data using 3-way ANOVA with the factors task domain, presentation condition and serial position (1 to 7). These curves are depicted in Figure 2, with the verbal task data in the upper panel and the spatial task data in the lower panel. We found main effects of presentation condition ($F(2,126)=66.82$, $MSE=.10$, $\eta 2p=.52$) and serial position ($F(2,756)=152.88$, $MSE=.06$, $\eta 2p=.71$). Two significant 2-way interactions, between presentation condition and serial position ($F(12,756)=3.36$, $MSE=.03$, $\eta 2p=.05$) and domain and serial position ($F(12,756)=26.02$, $MSE=.04$, $\eta 2p=.29$) were qualified by a significant 3-way interaction ($F(12,756)=2.70$, $MSE=.03$, $\eta 2p=.04$). The interaction between presentation condition and task domain was nonsignificant ($F(2,124)=0.92$, $p>.39$), as was the main effect of domain ($F(1,62)=.76$, $p>.38$).

To understand the 3-way relationship, we carried out separate 2-way ANOVAs for the spatial and verbal tasks. Examining Figure 2 suggests that the 3-way interaction could be due to differences between the effects of presentation condition on memory for the final item's position. In the both tasks, performance seemed lower in the dual-maintenance condition than in the other conditions for the first 6 items, but for the verbal task, performance in the uncued condition did not seem to be impaired for the final item[1]. To simplify our hypothesis testing, we included presentation condition and 2 levels of serial position, the average of the first 6 positions versus the 7th position, as factors in each ANOVA. We observed a significant interaction between presentation condition and serial position for the verbal task ($F(2,126)=17.81$, $MSE=.02$, $\eta 2p=.22$, $p<.001$), which must be due to the equivalent performance on the final item regardless of presentation condition, but no interaction for the spatial task ($F(2,126)=1.61$, $p>.20$). We observed the same pattern even when single-item lists were excluded (verbal reconstruction: $\eta 2p=.29$, $p<.001$; spatial reconstruction: $\eta 2p=.02$, $p>.26$).

1 Alternatively, this interaction could be due to the somewhat blunted serial position curves for some of the spatial task conditions. However, when we analyzed serial position separately for each domain and presentation condition combination, it was always statistically significant, with bowing reflecting significantly higher accuracy for the early and late items compared to the middle items.

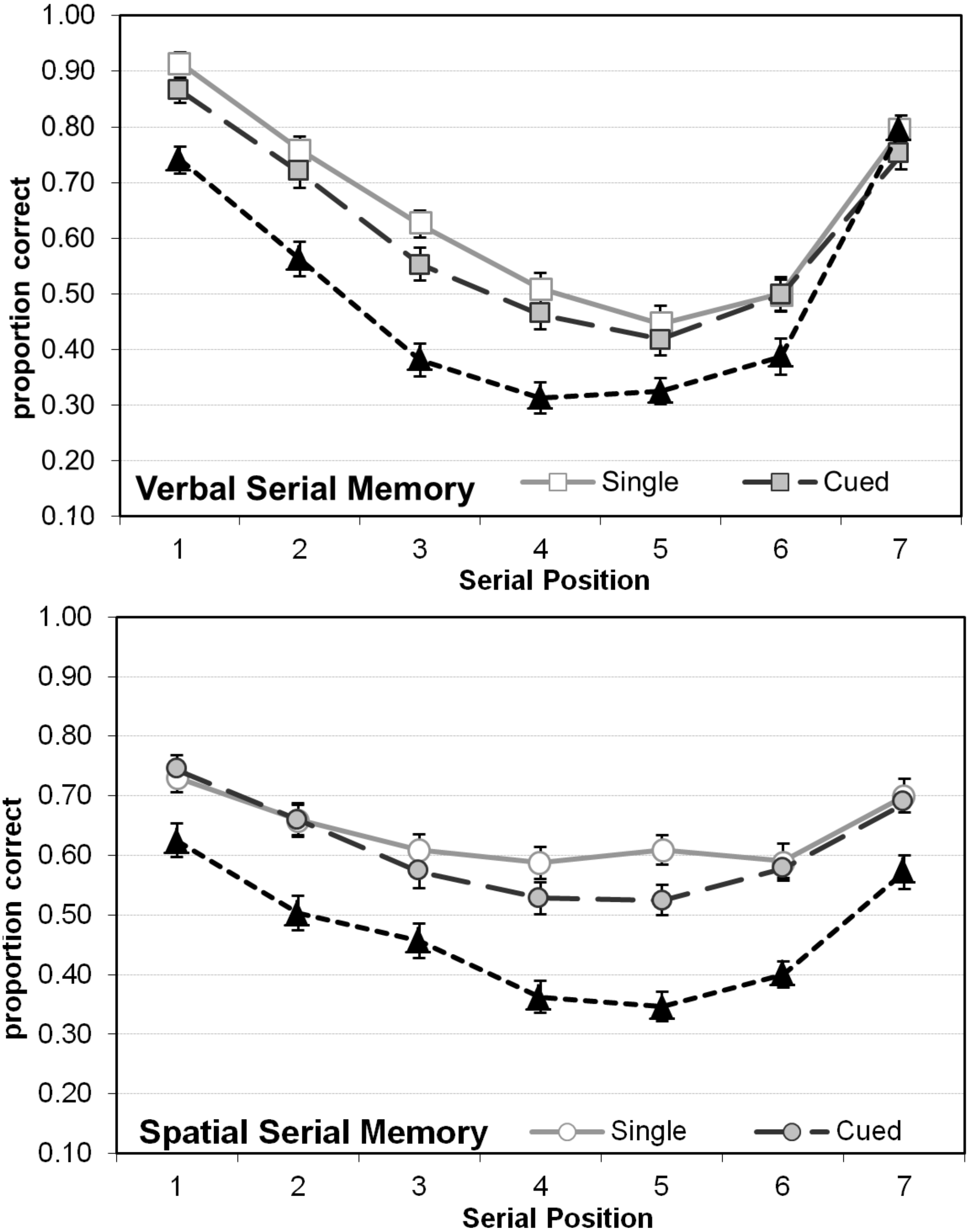


Figure 2. Serial reconstruction accuracy as a function of serial position for verbal sequences (upper panel) and spatial sequences (lower panel), 7-item lists, Experiment 1. Error bars are within-subjects standard errors of the mean (Cousineau, 2005) with Morey's (2008) correction.

2.3.3 Discussion

Reflecting the state of the published literature on this topic, we observed mixed evidence regarding the modularity of working memory resources. First, we observed clear dual-task costs for simultaneously maintaining verbal and spatial sequences. Simultaneously maintaining a verbal and a spatial sequence resulted in significantly worse memory performance than maintaining either sequence alone or maintaining either sequence while ignoring an interleaved sequence. This was true for spatial order reconstruction at each list length we measured, and for verbal order reconstruction at all but the 3-item lists. Examining serial position data in our longest lists, we found that the dual-task cost was present throughout the list in the spatial task but for the early and middle-list items only in the verbal task. The final verbal item was maintained without dual-task cost, but the final spatial item was not privileged in this manner. This suggests some difference in the resources available to maintain verbal and spatial information.

Identifying the source of the cost-free maintenance of the final verbal items is the key to theorizing about the asymmetric pattern we reported, and possibly to accurately characterizing modular resources in working memory. In two follow-up experiments, we consider two possible sources for this differential advantage. One possibility we considered was that the concrete nouns we used in the verbal lists activated long-term memory representations, while the spatial locations we used did not. Possibly, verbal information in our paradigms could be represented in at least two different manners, which helped to alleviate effects of dual-task interference. At least two popular conceptions of working memory include interfaces with long-term memory; in Baddeley's (2007) conception, activated long-term memory representations might be held in the episodic buffer, and in Cowan's (1995; 2005) framework, working memory is embedded in activated long-term memory. Items encountered more recently might be more strongly activated in long-term memory or more likely to be represented in the episodic buffer at the time of recall, which would improve performance for them. If verbal information generally is more likely to activate long-term memory representations than spatial information, then this might give them additional protection from interference and explain some of the asymmetries previously observed. To test this possibility, we conducted Experiment 2, in which we repeated Experiment 1 but also measured serial reconstruction for lists of pronounceable non-words. Although non-words might still be more salient than spatially located squares, they should be less likely to activate long-term memory representations than highly imaginable concrete nouns (Ward, Avons, & Melling, 2005).

We also considered the possibility that verbal and spatial representations differ in their access to a short-term store or rehearsal mechanisms, or possibly in the perseverance of information maintained in a short-term store. Evidence suggests that two separate processes, articulatory rehearsal and attentional refreshing, may support the maintenance of verbal information (Camos, Lagner, and Barrouillet, 2009), but the asymmetric pattern that we have found suggests that possibilities for temporarily representing spatial order information may be more restricted. We investigated this possibility in Experiment 3.

2.4 Experiment 2

2.4.1 Method

2.4.1.1 Participants

Thirty-six new participants recruited from the student population of the University of Groningen chose to take part in partial fulfillment of a course requirement. Two participants did not complete all experimental conditions due to equipment malfunctions leaving a final sample of 34 (28 women, 6 men, ages ranged 18-25 years, M = 20.82 years, SD = 1.89).

2.4.1.2 Apparatus, Stimuli, Design, and Procedure

The stimulus materials were the same as those in Experiment 1, except that new verbal stimuli, lists of comparable words and non-words, were introduced and only lists of four and seven items were included.

We selected 41 English two-syllable, six-letter nouns using Equiword (Lahl & Pietrowsky, 2006). We chose words that would contrast in strength of semantic content as much as possible with non-words: words with average frequency (London-Lund M = 7, SD = 11.2; Brown, 1984), high concreteness (M = 580, SD = 32; Paivio, Yuille, & Madigan, 1968) and high imaginability (e.g. window, palace; M = 587, SD = 31; Toglia & Battig, 1978). Our non-word list also included 41 two-syllable, six-letter pronounceable items (e.g. dublip, catter), selected using the English Lexicon Project (Balota et al., 2007). The recorded pronunciations for the words ranged from 239 to 962 ms (M = 629 SD = 123) and for the non-words from 480 to 935ms (M = 684, SD = 127).

Besides serial position, four factors were manipulated within-subjects: Presentation condition (single-presentation, cued, and uncued), task domain (verbal and spatial), word type (words and nonwords), and list-length (four and seven). However, the list length factor was unbalanced. We only included 4-item trials in the cued and uncued conditions, and we included four times as many 7-item trials as 4-item trials. We did not analyze the 4-item trials. Our main reason for including 4-item trials at all was to prevent participants from finding an experimental session filled with difficult 7-item lists too discouraging (Pratte & Rouder, 2009). Each participant completed 96 7-item trials, with stimulus presentation order randomized within-participants.

2.4.2 Results

Our goal with Experiment 2 was to test whether the interaction between task domain, presentation condition and serial position would remain with non-words rather than words as the verbal stimuli. As in Experiment 1, we begin with an analysis of the effect of presentation condition on overall serial reconstruction performance. We manipulated 4 factors, but will not dwell on a full 4-way ANOVA; instead, we restrict our analysis to 7-item lists and consider only nonword trials. We included word type in a preliminary analysis and found a significant interaction between domain and word type ($F(1,43)=11.46$, $MSE=0.61$, $\eta 2p=.26$, $p<.05$), caused by lower performance on verbal lists of nonwords ($M=3.16$ items correct per list, $SEM=.10$) than words ($M=3.59$, $SEM=.10$), but no difference in spatial reconstruction performance between the word and nonword conditions ($p=.13$). Because there appeared to be no effect of the type of phonological material maintained on spatial memory, the word trials only served to replicate Experiment 1's findings with two-syllable words. We therefore restricted the rest of our analysis to the trials with nonwords as memoranda.

2.4.2.1 Whole List Accuracy

We carried out a 2-way ANOVA with presentation condition and task domain on average number of correct responses in a trial for 7-item lists in the non-word condition. Means and standard deviations corresponding to this analysis can be found in Table 2. This analysis revealed main effects of presentation condition ($F(2,66)=45.85$, $MSE=0.36$, $\eta 2p=.58$, $p<.001$) and task domain ($F(1,33)=10.90$, $MSE=1.21$, $\eta 2p=.25$, $p<.003$). Their interaction was nonsignificant ($p=.52$). Performance was better overall on the spatial task ($M=3.57$, $SEM=.16$) than the verbal task ($M=3.06$, $SEM=.13$). This differs from Experiment 1, but it appears to be only due to measuring nonword memory performance instead of word memory performance; if word and nonword lists are both included in a similar analysis, the effect of task domain is not statistically significant ($p=.55$). Performance in the uncued trials, for which both stimulus sets must be encoded and briefly retained ($M=2.74$, $SEM=.15$), was worse than performance in the single-presentation ($M=3.64$, $SEM=.14$) or cued conditions ($M=3.56$, $SEM=.13$), which did not significantly differ from each other ($p=.42$). This result is broadly consistent with what we observed for 7-item word lists in Experiment 1.

	Spatial Task		Verbal Task	
	Words	Nonwords	Words	Nonwords
Single	3.94 (1.03)		4.37 (1.32)	3.33 (0.92)
Cued	3.83 (1.12)	3.82 (1.10)	4.05 (1.09)	3.29 (0.89)
Uncued	2.83 (1.07)	2.93 (1.09)	3.23 (0.89)	2.55 (0.91)

Table 2: Experiment 2, effects of cueing on word and nonword list memory.
Note. Mean number correct per 7-item lists (with standard deviations). N = 34.

2.4.2.2 Serial Position Accuracy

We proceeded to carry out an analysis of presentation condition as a function of serial position, running a 3-way ANOVA on mean proportions correct with domain, presentation condition, and serial position as factors. We included only nonword list trials in this analysis. Our primary interest was to attempt to replicate the interaction between domain, presentation condition, and serial position we observed in Experiment 1, which we attributed to preserved memory for the final item in verbal lists only. We reasoned that one explanation for this advantage could have been stronger semantic activation of verbal concepts than spatial locations, and if so, then the interaction may be weaker with nonword stimuli.

We observed significant main effects of each factor ($\eta 2p = .25$ for task, .58 for presentation condition, and .69 for serial position), but these were qualified by a significant 3-way interaction between task, presentation condition, and serial position ($F(12,396) = 1.97$, $MSE = .02$, $\eta 2p = .06$, $p < .05$). This relationship is depicted in Figure 3, which is strikingly similar to the pattern uncovered in Experiment 1. For spatial order reconstruction, the detrimental effect of encoding and maintaining a verbal list is present throughout the lists. However for verbal order reconstruction, the memory for the final items in the list is not significantly impaired by simultaneously maintaining a spatial list. To understand this interaction, we carried out separate ANOVAs for each task with presentation condition and serial position as factors, simplified by collapsing over the first 6 serial positions as in Experiment 1. Again, we observed a significant presentation condition by serial position interaction for verbal reconstruction ($F(2,66) = 9.11$, $MSE = .01$, $\eta 2p = .22$, $p < .001$), but no such interaction for spatial reconstruction ($F(2,66) = 2.82$, $\eta 2p = .08$, $p > .06$). The same pattern of inference appears even if only the cued and uncued presentations conditions are considered (verbal reconstruction, presentation by serial position interaction $\eta 2p = .36$, $p < .001$; for spatial reconstruction $\eta 2p = .08$, $p > .09$). Thus as in Experiment 1, it appears that the final verbal item is preserved from cross-domain interference, whereas there is no evidence that the final spatial item is preserved.

2.4.3 Discussion

Despite measuring memory for nonwords instead of nouns, Experiment 2 closely replicated the results of Experiment 1. As in Experiment 1, we consistently observed a cross-domain dual-task cost to both verbal and spatial serial reconstruction performance. We also replicated our finding from Experiment 1 of differing effects of concurrent maintenance on end-of-list items for verbal versus spatial stimuli. For spatial stimuli, concurrently maintaining verbal stimuli is detrimental throughout the list but for verbal stimuli, final items may be concurrently encoded and maintained while presumably also maintaining a spatial sequence, or at least shifting attention toward another stimulus. We therefore cannot strongly support the notion that the asymmetric preservation from cross-domain interference observed in Experiment 1 is attributable to superior support for verbal information from long-term memory.

With Experiment 3, we test another hypothesis to explain why verbal but not spatial lists exhibited this preservation from interference for the final item. Possibly, verbal information has access to a specialized store or rehearsal mechanism, and perhaps there is no equivalent structure for nonverbal information. This hypothesis is consistent with the reasoning of Camos et al. (2009; see also Barrouillet & Camos, 2010). Using a similar design and procedure as in Experiments 1 and 2, we added sensory suffixes after the presentation of the final memoranda. Even though our task called for serial reconstruction beginning with the first item remembered, we consistently observed recency effects in both tasks, and in the verbal task, no dual-task cost for the last item. If the mental representation of the last verbal item is maintained in a domain-specific sensory store, then the imposition of a sensory mask should induce a dual-task cost for the final item in the verbal list, making the effect of a concurrent task on verbal memory the same as it is to spatial memory. Such a pattern would suggest that the differences observed between interference with verbal and spatial serial reconstruction are attributable to differences in the availability or robustness of domain-specific short-term storage resources.

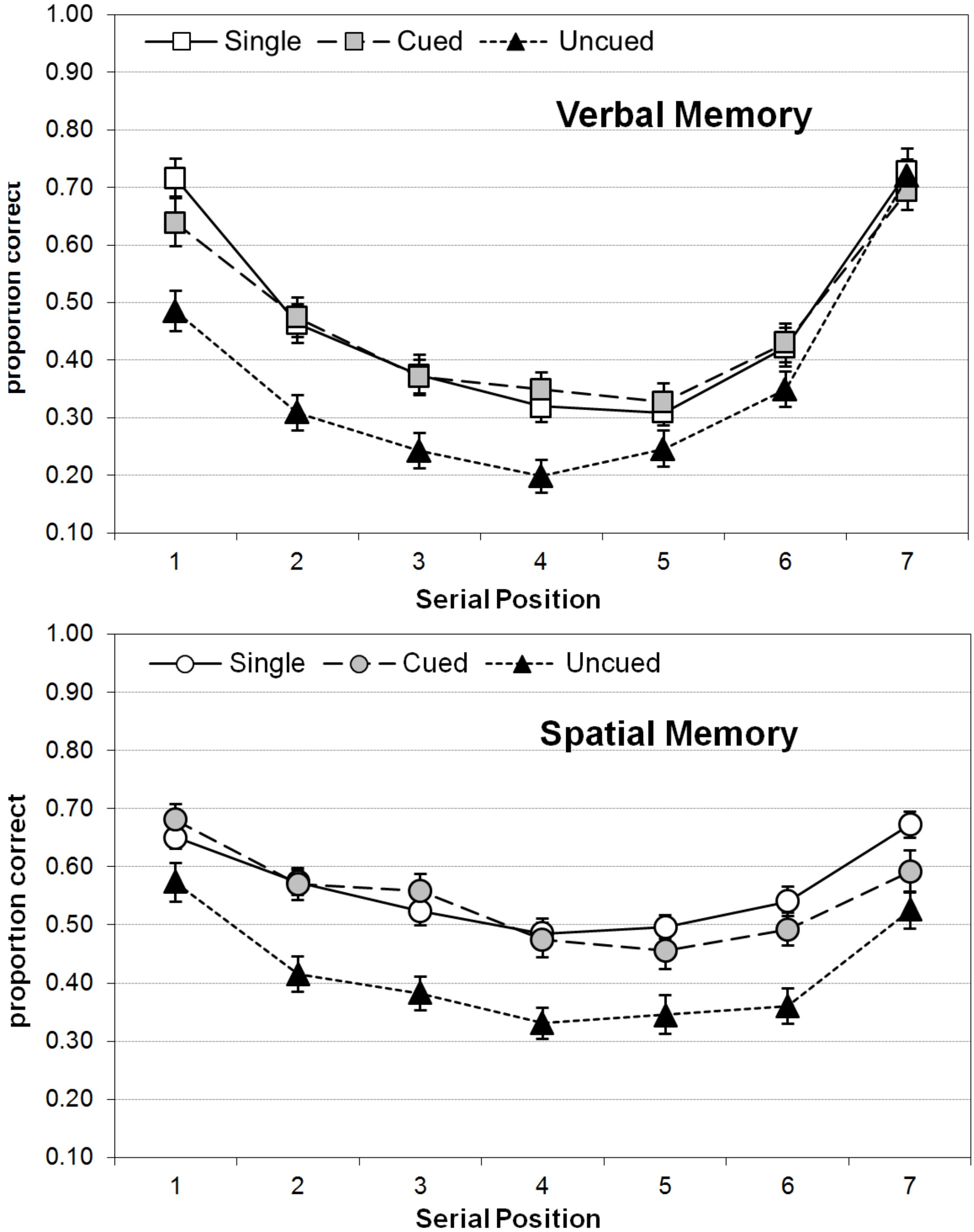


Figure 3. Serial reconstruction accuracy as a function of serial position for nonword sequences (upper panel) and spatial sequences (lower panel), Experiment 2. Error bars are within-subjects standard errors of the mean (Cousineau, 2005) with Morey's (2008) correction.

2.5 Experiment 3

2.5.1 Method

2.5.1.1 Participants

Thirty-seven students from the University of Groningen participated as part of their course requirements. One participant's data were removed due to near chance performance in the 4-item single-task conditions, leaving a final sample of 36 (27 women, 9 men, age ranged 19-31 years, M=21.22 years, SD=2.50). None of these participants took part in Experiments 1 or 2.

2.5.1.2 Apparatus, Stimuli, Design, and Procedure

The spatial memoranda were created and selected in the same manner as in Experiments 1 and 2. We selected verbal memoranda from the nonword list used in Experiment 2, because the proportions correct for nonwords were most similar to the proportions correct for spatial locations at the beginning and end of the 7-item lists in Experiment 2. We added auditory and visual suffixes after presentation of the to-be-remembered lists. The visual suffix was designed to occupy the entire area of the screen where spatial memoranda could have appeared, and consisted of a 675 x 525 pixel checkerboard-like image of black and white squares (75 x 75 pixels). The auditory suffix included all non-words presented during the current trial played back at the same time. In the cued and uncued conditions, both suffixes were presented simultaneously 500 ms after the offset of the last item. During single-task conditions, only the domain-specific suffix was presented, also 500 ms after the offset of the final list item. In all cases, presentation of the suffix lasted 1000 ms.

The experimental design was similar to that in Experiment 2. Four factors were manipulated within-subjects: task domain (verbal or spatial), presentation condition (single-presentation, cued, uncued), presentation order (square then nonword, or nonword then square), and list length (4 or 7). Combinations of these factors were presented randomly, for a total of 96 trials. Unlike in Experiment 2, in which we needed more 7-item trials to make up for the inclusion of an extra factor (i.e., words versus non-words), we were able to run an equivalent number of 4- and 7-item list trials, and included this factor in our analysis of overall number of correct responses per trial, in order to have an additional way to assess whether cross-domain costs were similar across presentation conditions and task domains.

2.5.2 Results

2.5.2.1 Whole list Accuracy

We carried out a 3-way ANOVA with task domain, presentation condition, and list length as factors. Descriptive statistics can be found in Table 3. We uncovered a main effect of task domain ($F(1,35)=28.38$, $MSE=1.84$, $\eta 2p=.45$, $p<.001$), showing that more correct responses were given for spatial ($M=3.48$, $SEM=.12$) than verbal ($M=2.79$, $SEM=.10$) serial reconstruction. Presentation condition also produced a significant main effect ($F(2,70)=89.41$, $MSE=.32$, $\eta 2p=.72$, $p<.001$), with the uncued condition ($M=2.62$, $SEM=.10$) resulting in fewer correct responses per trial than the cued ($M=3.35$, $SEM=.09$) and single-presentation conditions ($M=3.43$, $SEM=.10$), which did not significantly differ ($p>.20$). The effect of list length was nonsignificant ($p=.09$). Each interaction, including the 3-way interaction between task domain, presentation condition, and list length was statistically significant (3-way: $F(2,70)=4.20$, $MSE=.26$, $\eta 2p=.11$, $p<.02$; 2-way $\eta 2ps$ from .09-.31, $ps<.05$). This 3-way interaction was driven by differences in sizes of the effects of presentation condition on short and long verbal and spatial lists, not changes in directions of effects. We carried out separate ANOVAs for the verbal and spatial data, to better explain the significant 3-way interaction. For spatial lists, the cost of simultaneously maintaining a verbal list increased with list length, as evidenced by a significant 2-way interaction between list length and presentation condition for the separate ANOVA on spatial reconstruction performance ($F(2,70)=7.06$, $MSE=.32$, $\eta 2p=.17$, $p<.003$). For verbal lists, there was no interaction between list length and presentation condition ($p=.89$), and thus no evidence of an additional increase in cost as list length increased. These interactions show that both adding a concurrent task and increasing the number of to-be-remembered items impacts spatial memory more than verbal memory.

2.5.2.2 Serial Position Accuracy

As in Experiments 1 and 2, with auditory and visual suffixes a consistent effect of presentation condition was apparent, such that maintaining two lists simultaneously reduced performance compared to maintaining only one list. In Experiments 1 and 2, the final verbal items in each list, unlike the final spatial items, were preserved from interference. We considered whether an auditory suffix was sufficient to reveal a dual-task cost for verbal items at the end of lists.

We ran a 3-way ANOVA on mean proportions correct with presentation condition, task domain, and serial position as factors. In order to best isolate changes in our results due to the addition of sensory masks, we included 7-item lists from the stimulus presentation order in which the mask occurred directly after the final to-be-recalled stimulus; for the spatial reconstruction task, these were the lists in which a location was the final item prior to the mask and for the verbal task, these were the lists in which a nonword occurred just before the mask. This analysis is depicted in Figure 4. The critical 3-way interaction from our previous experiments was nonsignificant ($F(12,420)=1.13$, $\eta 2p=.03$, $p>.33$). The 2-way interaction between presentation condition and serial position was also nonsignificant ($F(12,420)=.70$, $\eta 2p=.02$, $p>.75$), providing no support for the hypothesis that end-of-list items differed from early-list items in the impact of cross-domain interference. We also observed main effects of presentation condition ($F(2,70)=33.21$, $MSE=.14$, $\eta 2p=.49$, $p<.001$), task domain ($F(1,35)=23.97$, $MSE=.32$, $\eta 2p=.41$, $p<.001$), and serial position ($F(6,210)=37.33$, $MSE=.07$, $\eta 2p=.52$, $p<.001$), and an interaction between task domain and serial position ($F(6,210)=3.34$, $MSE=.03$, $\eta 2p=.09$, $p<.02$). Other interactions were nonsignificant ($ps>.09$). Follow-up Bonferroni-correct comparisons confirmed that for both verbal and spatial serial reconstruction, performance in the uncued condition was significantly worse than performance in the cued or single-task conditions ($ps<.03$), which did not significantly differ ($ps>.64$)

	Spatial Task		Verbal Task	
	4	7	4	7
Single	3.64(.46)	4.06(1.30)	3.20(.61)	2.84(.95)
Cued	3.60(.50)	3.87(1.09)	3.19(.56)	2.74(1.03)
Uncued	2.99(.82)	2.74(1.05)	2.59(.70)	2.17(.84)

Table 3: Experiment 3 accuracy, by task domain, presentation condition, and list lengthNote. Mean number correct per list (with standard deviations). N=36.

2.6 Inter-task Correlations, Experiments 2 and 3

The consistent decrease in performance in the uncued conditions suggests that verbal and spatial serial memory share some resource. Another way we might examine this is by comparing patterns of correlations between verbal and spatial single-task performance and performance in the dual-presentation conditions. To do this, we calculated the average number of correct responses within 7-item lists for each participant in each presentation condition for the nonword and spatial location lists of Experiments 2 and 3. In the single-task conditions, these values may be considered estimates of verbal and spatial memory

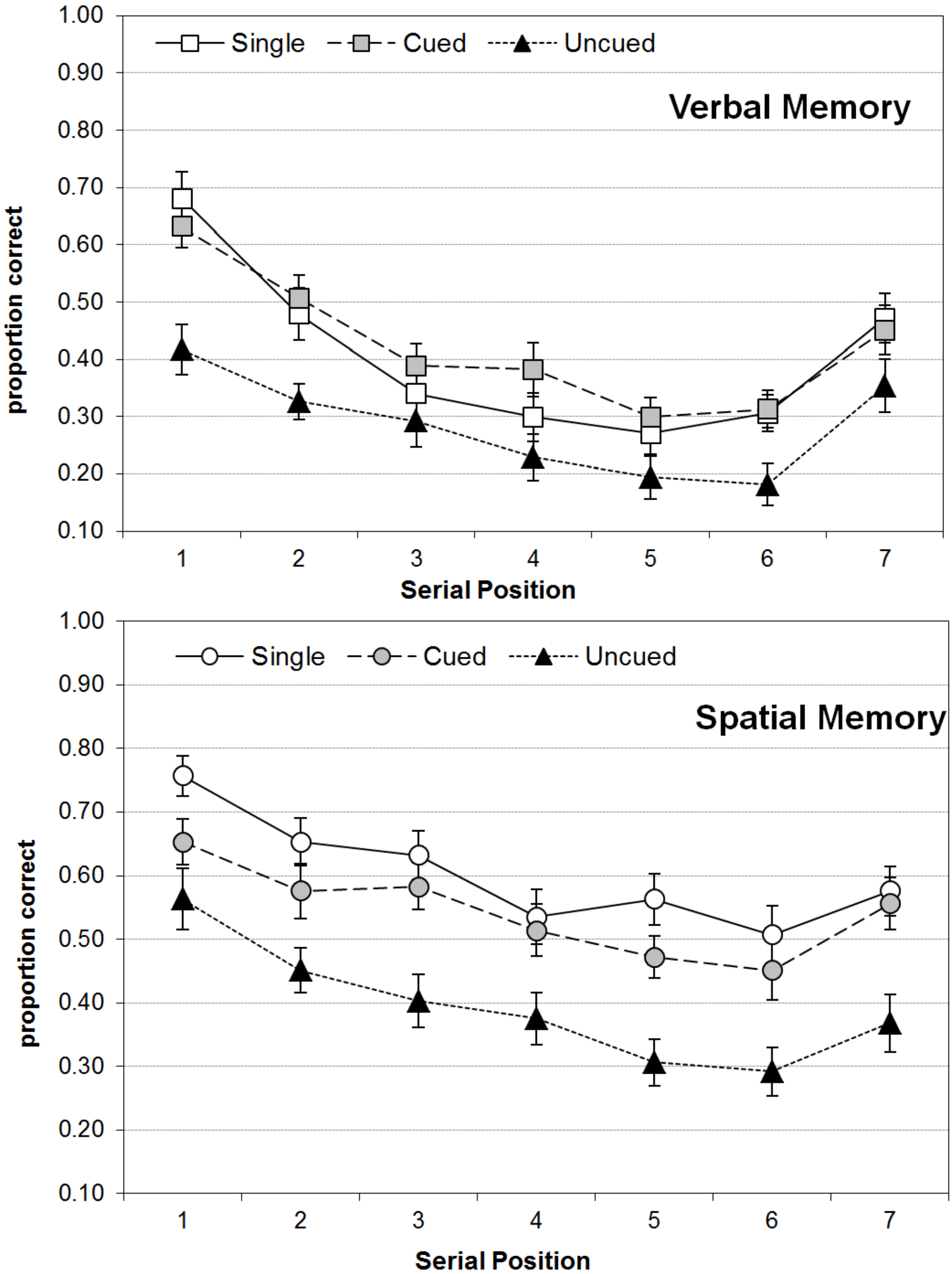


Figure 4. Serial reconstruction accuracy as a function of serial position for verbal sequences (upper panel) and spatial sequences (lower panel), Experiment 3. Error bars are within-subjects standard errors of the mean (Cousineau, 2005) with Morey's (2008) correction.

span, and we correlated these estimates with estimates from each of the dual-presentation conditions. Correlations are given in Table 4, where values below the diagonal are raw correlations, and those above the diagonal are partial correlations controlling for variance from the verbal or spatial single task conditions respectively. Consistent with the suggestion that some resources are shared between these tasks, verbal and spatial single-task performance correlated significantly. Though this relationship was statistically significant, the magnitude of the correlation (r = .32) does not suggest that these two tasks measure a single unique construct, so we calculated partial correlations between dual-presentation and single-presentation conditions, controlling for unique variance in verbal and spatial single-presentation performance. When variance with verbal serial memory was partialled out, spatial single-presentation performance still correlated significantly with verbal performance in the uncued dual-task condition. However, verbal single-presentation performance only correlated significantly with verbal dual-task performance after variations in spatial memory were controlled for.

Measure	1	2	3	4	5	6
Single-presentation conditions						
1. Spatial			.68*	.10	.63*	.24*
2. Verbal	.32*		-.16	.74*	.16	.53*
Dual-presentation conditions:						
3. Cued Spatial	.68*	.10				
4. Cued Verbal	.31*	.77*	.18			
5. Uncued Spatial	.67*	.32*	.59*	.25*		
6. Uncued Verbal	.37*	.58*	.20	.46*	.35*	

Table 4: Correlations between tasks and presentation conditions, Experiments 2 and 3
Note. Below the diagonal, raw Pearson 2-tailed correlations. Above the diagonal, partial correlations controlling for verbal (first row) and spatial (second row) performance in the single-list presentation conditions. N = 70.

2.7 Discussion

In light of the results of Experiments 1 and 2, the results of Experiment 3 suggest that verbal and spatial short-term memory differ in the availability of short-term storage resources. In each experiment we carried out, concurrently maintaining a verbal sequence interfered with memory for a spatial sequence and vice versa. At both list lengths we chose, we observed dual-task costs. Thus, throughout this project we have observed statistically significant dual-task costs for all but 3-item verbal lists.

This dual-task cost was present throughout the serial positions in the spatial reconstruction task. In an auditory-verbal version of the same serial reconstruction task, although memory was in general reduced by concurrent maintenance of a spatial list, the final item in the verbal list seemed to be unaffected by a concurrent spatial memory task in Experiments 1 and 2. Imposing an auditory suffix after the presentation of the final item ruined this preservation. We interpret this finding to indicate that recently presented verbal information is preserved in a short-term store in addition to the domain-general resource believed to underlie serial order memory, while visual-spatial information is not preserved in a comparable domain-specific store, or at least not for as long.

2.7.1 General Discussion

Although much research on immediate memory considers whether auditory-verbal and visual-spatial representations interfere with each other, this literature is full of conflicting evidence, varying from impressive examples of cross-domain multi-tasking (e.g., Cocchini, Logie, della Sala, MacPherson, & Baddeley, 2002; Logie et al., 1990) to evidence of strong cross-domain competition for storage resources (Depoorter & Vandierendonck, 2009; Saults & Cowan, 2007; Vergauwe, Barrouillet, & Camos, 2010) or equivalent interference from rehearsal suppression tasks designed to selectively engage domain-specific processes (Jones, et al., 1995). We chose to address this question by comparing performance on verbal and spatial serial order reconstruction tasks under single-task and cross-domain dual-task conditions.

Across three experiments, we consistently observed cross-domain interference between verbal and spatial serial reconstruction tasks when circumstances called for simultaneous maintenance of the two stimulus sets. We always observed dual-task costs for both verbal and spatial serial memory, except for in the shortest verbal lists. This confirms that verbal and spatial serial order memory tasks conflict substantially with each other, as previously observed (Depoorter & Vandierendonck, 2009). We add to previous findings by confirming that two cross-domain order tasks provoke an asymmetric pattern of interference, and testing the source of this asymmetry. Despite similar task demands, verbal order memory is less affected by concurrent memory of a spatial list than spatial memory is by a concurrently maintained verbal list. We learned that this asymmetry appears only for the final verbal list items, suggesting that verbal memory might be supported by a separate, domain-specific resource. Consistently with this idea, verbal list memory shows the same pattern of cross-domain interference from a concurrently held spatial list when an auditory suffix, which presumably disrupts the contents of an auditory sensory memory store, is imposed. This pattern of results is consistent with the possibility of a domain-specific verbal memory store but offers no support for a comparable domain-specific spatial memory store.

Our work is consistent with key elements of previous research supporting cross-domain sharing between verbal and spatial serial memory (Depoorter & Vandierendonck, 2009; Guérard & Tremblay, 2008; Jones et al., 1995) and helps to clarify discrepancies between these studies and others showing little or no cross-domain interference (e.g., Meiser & Klauer, 1999). Like Jones et al., we found evidence for shared resources between verbal and spatial short-term memory, but our evidence comes from concurrent verbal and spatial memory tasks rather than concurrent rehearsal suppression and memory tasks. Their clear effects of both verbal and motor suppression on verbal and spatial serial memory tasks have not clearly replicated (see Guérard & Tremblay, 2008), but if there were actually separate stores for verbal and spatial serial memory (separate even for maintaining order information, as Smyth and Scholey (1996) argued) one would not expect to observe substantial dual-task costs for concurrent maintenance of verbal and spatial lists, as we and others (Depoorter & Vandierendonck, 2009) have observed. Our data produced typical bowed serial position curves for verbal and spatial order reconstruction, as Guérard and Tremblay observed using similar tasks (see also Smyth, Hay, Hitch, & Hornton, 2005, who found typical serial position functions for faces), also consistent with the assumption of commonality across stimulus domains.

Although we have confirmed that interference occurs during simultaneous maintenance of verbal and spatial sequences, we cannot declare with certainty that simultaneous maintenance itself was the reason for dual-task impairment. Maintenance requires not only consolidation of the incoming memory items, but attending to them and encoding them, and in our design, switching attention quickly from encoding stimuli encountered aurally to stimuli encountered visually. We did not observe consistent dual-task costs in conditions in which verbal and spatial lists were both presented, but one dimension was cued prior to presentation. This makes it difficult to argue that processes involved in selective attending contribute much to the dual-task costs we observed. However, we cannot yet be sure whether encoding or consolidating the incoming stimuli is more responsible for the dual-task costs we observed. Prior research suggests that processes involved in simultaneously maintaining cross-domain stimuli, not simultaneously encoding stimuli provoke dual-task costs (Cowan & Morey, 2007), but judgments which do not require maintenance, such as those typically required by the processing task components of complex span tasks (e.g., Vergauwe et al., 2010), also seem to interfere with memory storage. Research from many cognitive paradigms suggests that interference from multiple sources can occur during the retention period in which a memory is consolidated or refreshed (e.g., Dewar, della Sala, Beschin, & Cowan, 2010; Morey & Cowan, 2005; Stevanovski & Jolicoeur, 2007).

We thus confirm several previous findings and observe a predicted asymmetrical pattern of interference, which could help to reconcile conflicting claims regarding resource sharing in working memory. Although we observed cross-domain interference, there are aspects of our data that cannot be elegantly explained by simply supposing that verbal and spatial materials strictly compete for a common storage resource. The asymmetries we observed prevent such a clear decision. Moreover, no model of working memory satisfactorily predicts and explains these asymmetries. Below, we describe how several prominent working models may accommodate this pattern.

2.7.2 Implications for models of working memory

The multi-component model of Baddeley (2007) proposes independent stores for auditory-verbal and visual-spatial information along with domain-general resources. Both of these stores are believed to benefit from the deployment of the domain-general episodic buffer and central executive, the latter of which is specifically presumed to support activities of the buffers during demanding tasks (Logie, 2011). Assuming that cross-domain interference occurs in this system because of competition for the domain-general components only, there is currently no reason to expect asymmetric patterns of cross-domain interference, as both verbal and visual-spatial representations are believed to benefit from the domain-general components. The multi-component model might account for the asymmetric patterns we observed by supposing that relationships between general attention resources and the domain-specific stores are not equivalent, perhaps explicitly hypothesizing that visual memory is more dependent on these general resources than verbal memory is. For example, one might suppose that rehearsal or refreshing of the contents of a visual-spatial buffer must take place more frequently than rehearsal or refreshing of the contents of a comparable domain-specific verbal store, thus frequently hogging the central executive's limited resources. More drastically, one might suppose a model with multiple components, but no specific visual-spatial store, as Phillips and Christie (1977) proposed. In our studies, the time between presentation and recall of any particular item would have been many seconds; it is thus perhaps most cautious to suppose that any domain-specific spatial representations could not be maintained without sustained attention during so long a period. However, in support of the Phillips and Christie hypothesis, we observed cross-domain interference at all list lengths in the spatial serial reconstruction task, not only the demanding levels for which the central executive would presumably be recruited.

Alternatively, one might also suppose a preference for attending to verbal stimuli, honed by life-long practice (Logie, Cocchini, della Sala, & Baddeley, 2004), but this assumption can be adopted much more parsimoniously within a perceptual-gestural account of memory (e.g., Hughes, Marsh, & Jones, 2009), which might explain greater verbal-list independence from cross-domain interference on account of the availability of speech-based motor processes. Speech-based motor processes may be arguably more practiced and distinct than the motor movements that distinguish several spatial locations all situated within a limited visual field, which might require a greater share of attention to initiate. However, one weakness of these possibilities is that they would suppose that cross-domain dual-task costs should be smaller for verbal serial memory than for spatial serial memory throughout a list, whereas we find clear differences in the size of cross-domain costs only for the final items in a list.

Embedded models of working memory and attention (e.g., Cowan, 1995; 2005; Oberauer, 2002; Oberauer & Kliegl, 2006) posit that working memory is a subset of long-term memory, characterized by unusually strong activation. The most strongly activated objects occupy the focus of attention, whose capacity is constant regardless of the stimulus modality of its contents. Other, less highly activated information might be retrieved into the focus of attention over the course of some cognitive activity. Emphasizing common structures for memory representation across domains, these models are more parsimonious than Baddeley's multi-component model, but do not clearly explain why dual-task performance is sometimes so resistant to interference. Embedded models do not necessarily predict the asymmetric pattern we observed, but could explain it by supposing that auditory-verbal information remains activated longer than visual-spatial information, and is therefore more likely to be accessible by the focus of attention even after a delay.

Like the embedded models, the Time-Based Resource Sharing (TBRS) model of Barrouillet, Bernardin, and Camos (2004) posits a single attentional resource that must be shared between multiple mental operations. The TBRS model posits that the focus of attention might be briefly deployed to refresh activated representations in between operations of a task. Interference is then determined by the cognitive demand of a concurrent task: if a task requires the constant application of the focus of attention, then previously activated information will become weakened and less likely to be retrieved. Similarly to the embedded models, TBRS could explain our asymmetric interference by supposing that visual-spatial representations are more susceptible to time-based decay than auditory-verbal ones, and thus require more frequent application of attentional resources to maintain activation. Recent proposals also suggest that a resource capable of verbal rehearsal could be supposed in addition to the standard TBRS account (Barrouillet & Camos, 2010; Camos, et al., 2009), which would be consistent with our results. However, an account of how these two resources might interact is not yet thoroughly described.

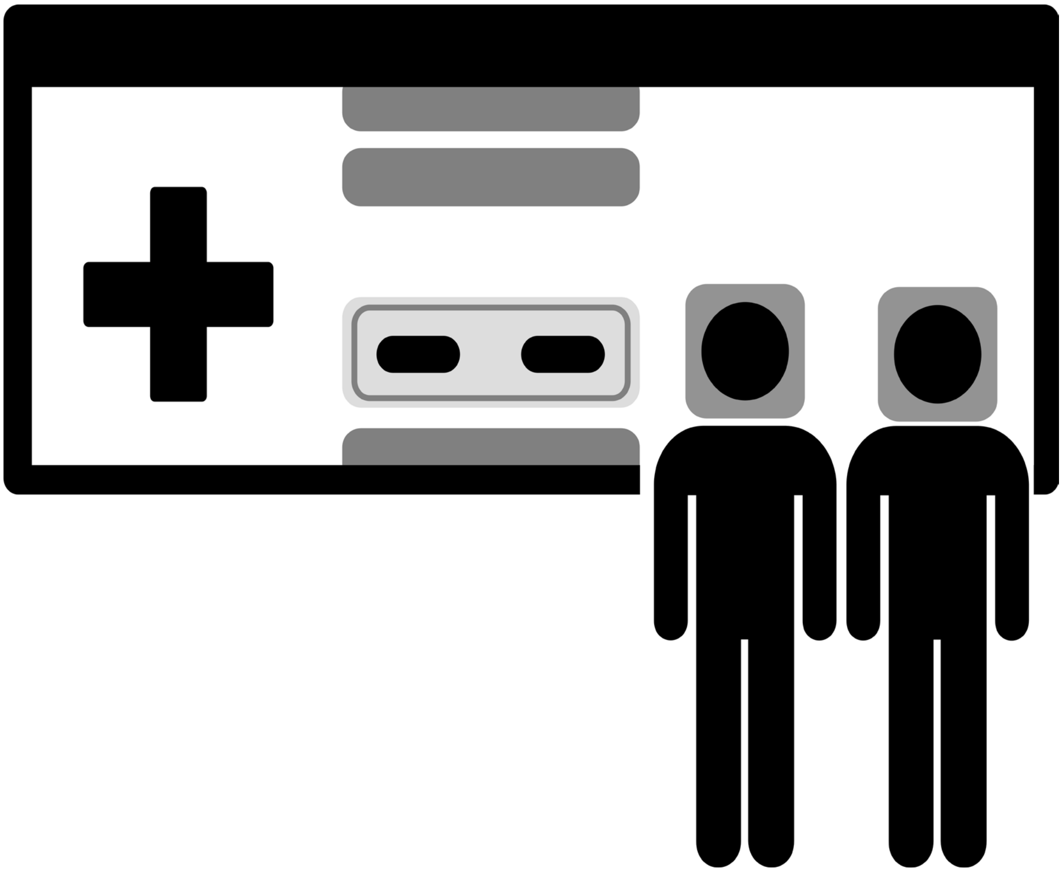
We believe that the assumptions of the extended TBRS account merit further theorizing and testing; particularly, further study is needed to better specify this hypothesis. Currently, it is difficult to determine whether the extended TBRS account and a truncated version of Baddeley's multi-component model would make unique predictions. One prediction upon which they may differ is in the total amount of information that can be concurrently maintained. The extended TBRS account, as delineated by Camos et al. (2009), conceives of the extra verbal resource as a rehearsal mechanism that acts upon stored information, not a separate store, whereas in Baddeley's (2007) account, domain-specific and domain-general stores are both proposed, and perhaps may be simultaneously used. These two conceptions could lead to differing predictions about the total amount of information stored at any one time. Ultimately, a system with fewer modules than the multi-component model but incorporating embedded attention and storage components may explain divergent dual-task data better than the currently proposed frameworks, but more hypothesis testing is necessary before we can declare precisely how such a framework ought to be specified.

2.8 Conclusions

These studies help to clarify previous research about interference between verbal and spatial serial memory, which has varied so much that some researchers endorse complete sharing between verbal and spatial memory while others insist on nearly independent verbal and spatial systems. Although clear effects of interference were observed between verbal and spatial serial memory tasks, our results also indicate that verbal and spatial storage differ in their reliance on domain-general resources. These findings endorse emerging assumptions for models of working memory that may ultimately produce a compromise between models that focus on domain-specificity and models that stress domain-general resources.

2.9 Appendix

Experiment 1 Words	*Experiment 2 Words*	*Experiment 2 & 3 Nonwords*
belt	anchor	bagans
cage	basket	catter
chess	battle	covart
clay	butter	dachel
cream	button	dector
drum	carpet	dublip
egg	cellar	erdest
farm	cherry	flogan
fork	circle	fluing
fruit	closet	germed
gate	coffee	gidled
ghost	corner	grager
gift	dancer	griple
golf	dinner	herped
hill	doctor	hilder
map	dollar	lacket
myth	engine	latten
road	figure	lerman
room	forest	mecamp
sand	garden	menant
seat	hammer	migwig
shirt	kettle	minger
shoe	lawyer	mising
snail	letter	mogleg
soap	locker	ounwit
stone	nickel	outrin
tea	office	partar
tire	orange	pliver
trash	palace	prewap
trend	pencil	rapimt
wave	pillow	rostal
wing	pocket	seword
wood	powder	slared
year	shower	slosed
	sister	soners
	supper	spavel
	tennis	stimed
	ticket	talmid
	valley	tartle
	window	toplin
	yellow	unh



CHAPTER 3 ATTENTIONAL CONTROL

A version of this chapter has been submitted as Mall, J. T., Morey, C. C., M. Wolff, F. Lehnert. Working memory capacity is more than just attentional control: Evidence from eye-movements during a visual working memory task.

3.1 Abstract

Selective attention and working memory capacity (WMC) are related constructs, but debate about the manner in which they are related remains active. One elegant explanation for this relationship is that the efficiency of filtering irrelevant information is driving WMC differences. We examined this explanation by relating WMC (as measured by complex span tasks) to accuracy and eye movements during visual change detection tasks with different degrees of attentional filtering and allocation requirements. Our results did not indicate filtering differences between high and low-WMC groups in the direction predicted by the attentional filtering hypothesis. We instead observed positive or null relationships between WMC and the time people spent looking at irrelevant information. These findings support a more complex interpretation of the relationship between WMC and selective attention and suggest that individual differences in memory capacity, not only filtering efficiency, influence performance.

3.2 Introduction

Working memory capacity (WMC), the ability to concurrently store and process information, is strongly correlated with performance on a large range of cognitive tasks with low memory demands (Hutchison, 2007; Jarrold & Towse, 2006; Unsworth, Schrock, & Engle, 2004), scholastic achievements (Alloway, 2009) and common cognitive failures (Unsworth, Brewer, & Spillers, 2012). Two main types of theories have been put forward to explain these relationships. One type emphasizes the individual differences in attentional abilities (Engle, Kane, & Tuholski, 1999; Kane et al., 2004; Kane, Conway, Hambrick, & Engle, 2007) whereas the other emphasizes individual differences in storage capacity (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Cowan et al., 2005). Both types of theory aim to explain individual differences in a number of key phenomena in selective attention.

A compelling illustration of relationships between individual differences in WMC and selective attention occurs in the cocktail party effect, a phenomenon in which the own name is noticed in a nearby conversation while one is engaged in a different conversation at a cocktail party. In the laboratory, Conway, Cowan and Bunting (2001) had participants perform a dichotic listening task in which different streams of words were presented to each ear and the relevant stream had to be repeated aloud. Low-WMC individuals were found to notice their own name in the irrelevant stream much more frequently than high-WMC individuals, indicating a deficit in selectively attending to the relevant stream (Conway et al., 2001). When participants were asked instead to divide their attention between two streams and report immediately when they noticed their own name, high-WMC individuals reported hearing their own name more often than low-WMC individuals, demonstrating that high-WMC enables the flexibility to focus attention to the exclusion of irrelevant information or the effective division of attention between two relevant sources (Colflesh & Conway, 2007). High-WMC individuals seemed able to flexibly ignore irrelevant information or divide their attention between multiple sources of information, depending on what the situation called for.

There is also evidence that high-WMC is associated with effective selective attention towards visual information. Vogel, McCollough, and Machizawa (2005) used a visual change detection paradigm that featured relevant and irrelevant items. Utilizing the amplitude of contra-lateral delay activity as a measure of memory storage (Vogel & Machizawa, 2004), Vogel et al. estimated how many items participants were committing to memory during a visual change detection task. When both relevant and irrelevant items were briefly presented, participants with high memory performance exhibited contra-lateral delay activity amplitudes similar to storing only the number of relevant items whereas participants with low memory performance seemed to store both relevant and irrelevant items. These and similar findings (e.g. McNab & Klingberg, 2008) have been interpreted to mean that low-WMC individuals might not have a smaller storage capacity per se, but instead overload working memory with irrelevant information. Since the irrelevant information that low-WMC individuals inevitably encode is never tested, they only seem to have low capacity (Awh & Vogel, 2008).

However, relationships between effective selective attention and WMC are not always apparent in situations designed to evoke them, suggesting that boundary conditions for relationships between WMC and selective attention still need to be clearly articulated. Irrelevant speech effects, the decline in performance when listening to irrelevant auditory stimuli during a memory task, do not show consistent relationships with WMC. The association between irrelevant speech effects and WMC has often been found to be weak (Elliott & Cowan, 2005) or absent (Beaman, 2004); Beaman only found the predicted relationship between irrelevant speech effects and WMC, in which individuals with low-WMC showed a larger irrelevant speech effect, when the irrelevant speech was semantically related to the to-be-remembered items. In general, WMC has only been found to strongly correlate with the deteriorating effect of unexpected, infrequent auditory distractors but not continuous and predictable distraction (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2012; Sörqvist, 2010). Some evidence suggests that the same boundary conditions also limit visual selective attention (Fukuda & Vogel, 2009). Thus, the association between WMC and selective attention depends on distractor properties. Counter to what the strictest interpretation of an attentional filtering theory would predict, low-WMC individuals were able to cope with distractors as long as they appeared predictably and continuously.

A possible explanation for the disparate relationships between WMC and selective attention comes from the notion that a key difference between low and high-WMC individuals is their propensity to actively maintain task goals. In some situations, goal maintenance can provide the crucial information needed to quickly recover from an attentional lapse and thereby prevent an error. For example, when a task required participants to look away from a flashing stimulus by performing an anti-saccade, low-WMC individuals made more errors and were consistently slower to inhibit the reflexive pro-saccade towards the flashing stimulus, even when minimal additional processing was required (Kane, Bleckley, Conway, & Engle, 2001; Unsworth et al., 2004). However, no differences between low and high-WMC individuals were apparent in a pro-saccade task, suggesting the critical difference is not in attending, per se. Similarly, low-WMC individuals exhibited a bigger Stroop effect than high-WMC individuals, but only when incongruent trials were rare (Hutchison, 2011; Kane & Engle, 2003; Morey et al., 2012). A task context with frequent congruent trials (e.g., 75%) allows participants to forget that the task goal is to name the ink color, rather than read the word; on congruent trials, performing either would lead to the correct response, and with mostly congruent trials, there is thus little cost to disregarding the correct goal. However, manipulating task context alone is not sufficient to produce the predicted relationship between conflict resolution and WMC. Morey et al. (2012) found no WMC-related differences in cross-modal versions of the Stroop task. The cross-modal tasks featured auditory incongruent words that were presented simultaneously with to-be-named colored squares. The cross-modal version therefore involved Stroop-like semantic conflicts but no conflict between color-naming and reading. Since such tasks did not produce WMC-related differences, Morey et al. argued that two criteria were necessary for WMC-related differences in conflict resolution to emerge: 1) the task context must encourage active maintenance of the task goal (i.e., naming the ink color), and 2) it should not be possible to reinstate the goal from the task materials themselves, as is the case with cross-modal Stroop; the participant must recover the goal by retrieving it.

Taken together, these selective relationships between attentional control and WMC indicate that the true relationship between these constructs cannot be simply that WMC reflects only individual differences in attentional filtering (Awh & Vogel, 2008). The extant data are not consistent enough to support this idea. We set out to re-examine relationships between WMC and selective attention toward visual stimuli in order to try to further disambiguate these concepts. Although several studies have previously investigated relationships between visual selective attention and memory capacity (e.g., Fukuda & Vogel, 2009; McNab & Klingberg, 2008; Vogel et al., 2005), there are limitations to their interpretability. First, these studies typically rely on capacity estimates from a visual change detection task as the sole WMC indicator, while performance on the same task also generates the measures of filtering efficiency, whether these are behavioral or neural (but see Fukuda & Vogel, 2009, who do show generalization across a broader range of tasks). When correlations are observed between WMC and filtering efficiency, the correlations are striking, which is perhaps not surprising considering that both measures are usually derived from various aspects of performance on the same task. If similar relationships were uncovered between filtering efficiency during visual change detection and another measure of WMC, such as a complex WM span task (Unsworth et al., 2005), then interpretation of the meaning of the correlations would be stronger even if the correlations were somewhat weaker.

Second, though there seems to be an emerging consensus that low-capacity individuals are only especially susceptible to involuntary attentional capture (e.g. Hughes et al., 2012; Sörqvist, 2010) this explanation does not entirely fit with the idea that low-WMC individuals helplessly store irrelevant items during visual change detection tasks. In these paradigms (e.g. Cowan et al., 2010; Fukuda & Vogel, 2009; Gold et al., 2006; Vogel et al., 2005), participants are made aware of which items are most relevant and which are to-be-ignored. The irrelevant items are typically not part of the same set as the relevant ones; for instance, relevant items might differ from distractors in color (McNab & Klingbery, 2008; Vogel et al., 2005) or shape (Cowan et al., 2010; Fukuda & Vogel, 2009). Thus one would expect for low-WMC individuals to have trouble focusing on the most relevant stimuli only if WMC influences voluntary attentional control.

There is also some reason to doubt the extent to which irrelevant storage affects task performance. Cowan et al. (2010) compared WMC as measured with a visual probe recognition task in children and adults, including conditions that required attentional selection for optimal performance. Young children are known to have lower WMC than older children and adults (e.g., Cowan et al., 2005), yet even the youngest group of children in Cowan et al.'s sample were capable of following the attentional selection instructions, which indicated that they should focus more on remembering one particular category of colored shape. Cowan et al. concluded that even young children with smaller WMC could filter efficiently under conditions in which their storage capacity was not exceeded. Similarly, patients with schizophrenia, who demonstrate lower WMC than healthy controls, nonetheless show no clear difference in the ability to selectively attend to particular objects within a to-be-remembered visual array (Gold et al., 2006).

Furthermore, requiring maintenance across only a short retention interval (900ms) should actually require little of the sustained maintenance of attentional focus that should be necessary to detect WMC differences. For example, in a study by Poole and Kane, (2009) participants searched a predetermined grid of which some locations were cued as likely to contain a target. Maintaining the fixation on the cues was required over a short (300ms) or long (1500ms) delay. Low-WMC individuals were slower when distractors were present, but only when the delay was long. Thus WMC was associated with the filtering of irrelevant information, but only when attentional focus needed to be maintained over some time.

To evaluate the relationship between WMC and selective visual attention we used eye-tracking to elucidate how individuals dealt with irrelevant information. Presumably, if individuals differ in their ability to selectively attend only the most relevant items in an array, we would discern this difference in gazes. Because eye-tracking has been found to be a reliable tool for measuring retrieval (Ferreira, Apel, & Henderson, 2008; Tremblay, Saint-Aubin, & Jalbert, 2006), we recorded eye movements during the retention interval as well as during the memory display, when the stimulus array was present onscreen. We used a visual change detection paradigm in which arrays included equal numbers of circles and triangles, and for each participant one of these shape categories was randomly assigned to be the predominant shape. We included blocked conditions that varied in how frequently the predominant shape would be tested in Experiment 1, and varied how much reward a correct response toward a probe of each shape garnered in Experiment 2. In both cases, inefficient selective attention could be assessed by comparing accuracies and gaze toward predominant shapes versus less relevant shapes. We extended the retention interval to three seconds to require sustained attention during maintenance and allow for increased variability in looking behavior. Participants were selectively recruited for these eye movement studies on the basis of their performance on two complex working memory span tasks, which they completed in a separate experimental session weeks earlier. Complex span tasks were frequently used to determine WMC in much of the selective attention research cited above.

3.3 Experiment 1

Experiment 1 featured three conditions presented in separate blocks, depicted in Figure 1. (A) In full-Set blocks, shapes from both categories were to be attended and both were tested equally often. Full-Set trials were used as a baseline measure of visual array task performance. (B) In half-Set blocks, only one shape was tested and thus the other could be ignored with no cost to performance. Eye movements during Half-Set performance served as an estimation of filtering efficiency because selective attention towards the attended shape was required. (C) In ratio-Set blocks, one shape was tested twice as often as the other shape. We considered both predominant and infrequent item performance within the Ratio-Set, with both accuracy and fixation duration (i.e., dwell time) used to measure the strategic allocation of attention.

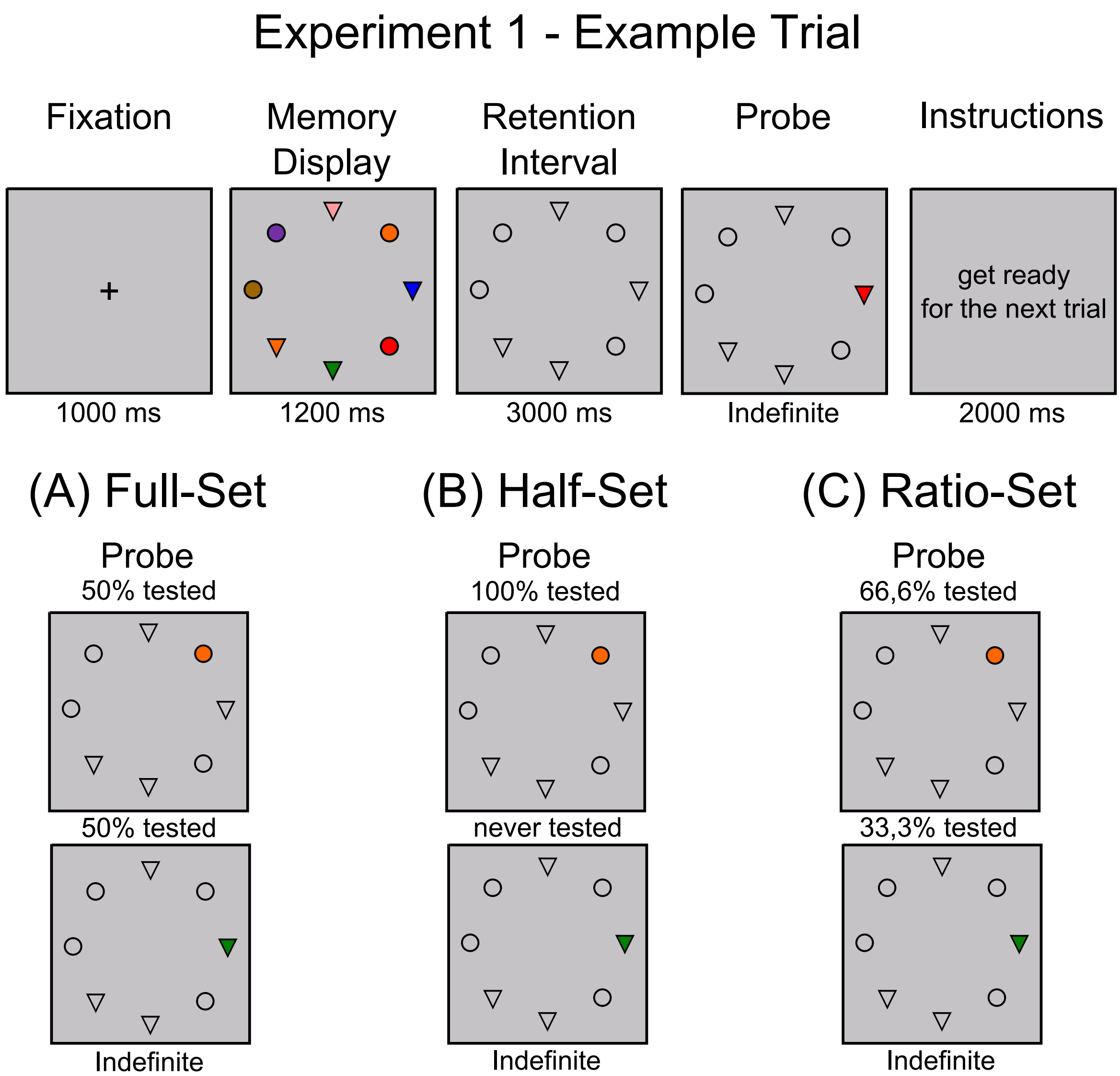


Figure 1. Schematic illustration of the visual task conditions and set-sizes. (A) Full-Set, all shapes are tested (B) Half-Set, one shape is always tested (C) Ratio-Set, one shape is tested 66,6% and the other 33,3% of the time. For this schematic, the predominant shape is a circle; which shape was predominant varied by participant. Changes occurred to 50% of probes in each block.

According to the strong interpretation of the attentional filtering view, low-WMC individuals were expected to fail at ignoring irrelevant items in the Half-Set, leading to lower performance and excessive fixation time on irrelevant items compared to high-WMC individuals. In the Ratio-Set, performance on the infrequently tested items was expected to be better for low-WMC individuals since they should have inadvertently stored some of the infrequently-tested items (i.e., Awh & Vogel, 2008); low-WMC individuals should likewise fixate infrequently-tested items more often than high-WMC individuals. However if individual differences in storage capacity also play a role in determining visual array task performance, high-WMC capacity individuals might choose to divide their resources between the predominant and the infrequently-tested items in the Ratio-Set to enhance their overall performance.

3.3.1 Method

3.3.1.1 Participants

Seventy-one students from the University of Groningen (43 women, 28 men, age 18-33, M = 20.76, SD = 2.18) participated as part of their course requirements or for an honorarium of €14. One participant was excluded from all analyses due to color blindness and an additional 11 participants were excluded from the dwell time analysis due to erroneous calibration of the eye-tracker in at least one experimental block. The study was approved by the local ethics committee and participants gave written informed consent before the study began. All participants were fluent English speakers.

3.3.1.2 Working Memory Capacity screening

Participants were screened using two complex working memory span tasks in a 60-minute session at least two weeks prior to the main experimental session using computerized versions of the operation and symmetry span tasks (Unsworth, Redick, Heitz, Broadway, & Engle, 2009; Unsworth, Heitz, Schrock, & Engle, 2005). In operation span, participants were asked to remember serially-presented consonants, interleaved with a secondary task, judging the accuracy of math equations. For each trial, different letters (F, H, J, K, L, N, P, Q, R, S, T, and Y) and equations were presented 3-7 times before participants recalled the letters in order. In symmetry span, participants were instructed to remember serially-presented locations of red squares in a 4x4 matrix interleaved with a secondary task, in which participants judged whether a block pattern was vertically symmetrical. In each trial different locations and block patterns were presented 2-5 times, before participants recalled the locations on the matrix in order. An 85% correct criterion for performance on the secondary task (i.e., the math equations and symmetry judgments) was required to take part in the following experiment. Performance was measured using the partial storage score (as recommended by (Conway et al., 2005)), the sum of items recalled in the correct serial position for a maximum score of 75 for operation and 42 for symmetry span. Scores from both tasks were added to create a WMC composite score. Thus low, mid and high-WMC individuals created using a split of the composite score with scores below 81 or above 99, respectively. The cut offs were based on a large screening sample (N = 1014) of first year psychology students. We recruited high and low-WMC individuals from the extreme quartiles plus individuals from the middle quartiles. Score distribution was comparable to established norms (Redick et al., 2012) showing a similar clustering at the high end of the distribution of WMC scores.

3.3.1.3 Apparatus and stimuli

The visual memory task was presented on a 48.26 cm diameter IIlyama Vision Master Pro 513 CRT monitor, at a resolution of 1280 x 1024 and a refresh rate of 60Hz. Presentation was controlled using E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Eye movements were measured at a rate of 1000 Hz using an SR Research EyeLink 1000 with 0.01° spatial resolution. Distance between monitor and chinrest was kept constant at 67 cm and the distance between chinrest and camera was always 50 cm. A Microsoft Sidewinder gamepad was used for response collection.

All stimuli were presented against a grey background (HTML value: C0C0C0). Depending on condition and trial, two, four or eight colored triangles and circles with black outlines were randomly presented at eight fixed positions arranged in a circle around the center of the screen (Figure 1.). Per trial, half of the shapes were circles and the other half triangles. Memory and probe shapes were filled with one of nine colors: white (FFFFFF), red (FF0000), orange (FF6600), yellow (FFFF00), green (008000), blue (0000FF), purple (7030A0), brown (996600) or pink (FF9999). Colors were randomly selected within each shape category independently; a trial could thus have circles and triangles with the same color. During the retention interval only the black outlines of the shapes were shown to enable consideration of gazes during retention as reflecting rehearsal (Ferreira, Apel, & Henderson, 2008; Tremblay et al., 2006). The circular arrangement of invisible positions in which the shapes were presented subtended 7.51° and each stimulus' location was 3.76° from the center of the screen. Shapes were sized to fit inside an invisible rectangle which subtended 0.79° and served as the landing area for eye fixations.

3.3.2 Procedure

After signing the informed consent, an experimenter explained the visual task requirements. Each session began with a six-item color blindness screening (Ishihara, 1966) and six supervised practice trials with accuracy feedback. Before each experimental block, the eye tracker was manually calibrated to the right eye.

Figure 1 depicts the timing of events within a trial. Each trial began with a 1,000-ms fixation cross (+), followed by a 1,200-ms memory display of two, four or eight objects, followed by a 3,000-ms retention interval of the objects' outline followed by a probe display with the objects' outlines and one colored shape, which remained onscreen until a response was collected. Participants were asked to indicate via button press whether the color of the shape on the probe display was the same as or different from the shape at the same location on the memory display. The color of the shape changed on 50% of trials. After the response, a 2000-ms screen appeared with the text "get ready for the next trial". No accuracy feedback was given on experimental trials.

Each block featured one of three within-subjects probe conditions (see Figure 1). Each participant was assigned a predominant shape, which was counterbalanced between-participants. In (A) Full-Set blocks, participants were informed that any shape could be tested. Full-Set trials featured two, four or eight shapes. In (B) Half-Set blocks, participants were informed that only the predominant shape would be tested and that the other shape should therefore be ignored. Half-Set trials featured four or eight shapes. In (C) Ratio-Set blocks, participants were informed that the predominant shape would be tested most frequently but the other shape would be tested occasionally. Participants were not informed about the exact percentages of predominant and other-shape tests (66.6% and 33.3% respectively). Ratio-Set trials featured four or eight shapes. All blocks were presented in the same order to each participant (Full-, Half-, Ratio-, Ratio-, Half- and Full-Set), with repeated blocks in reverse order to minimize influences of practice and fatigue on between-block differences. Between the third and fourth block participants took a mandatory break of 10 minutes; breaks were also allowed at the participant's discretion between each block. The complete session, including setup and debriefing, lasted 105 minutes.

3.3.3 Results

We employed Bayesian analysis of variance (Rouder, Morey, Speckman, & Province, 2012) to examine WMC group differences in accuracy. This was done using the freely available R package BayesFactor (version 0.9.2). This technique allows for meaningful interpretation of null results, which is especially important here because the predicted relationship between WMC and accurate responding to predominant and infrequently-tested shapes was not present. Inference using Bayes factors is also free from the interpretative difficulties associated with the criterion logic of p-values. We also provide outcomes from traditional methods for the correlational analyses in order to facilitate comparisons with previously published results.

3.3.3.1 Visual recognition accuracy

Proportion of correct responses was computed as the dependent variable. Descriptive statistics for all experimental conditions are given in Table 1, but inference on accuracies was limited to the Ratio-Set to test whether WMC predicts the inability to filter irrelevant information. Assuming the attentional filtering hypothesis, we expected higher performance on infrequently tested items for low-WMC individuals than for high-WMC individuals. We therefore compared accuracy in the Ratio-Set with test likelihood (predominant (66.6%) or infrequent (33.3%)) and set size (4, 8) as within-participants variables and WMC (High, Middle and Low) as a between-participants variable. Bayes factors were estimated for all combinations of the three possible main effects and their interactions, and calculated with 1,000,000 Monte Carlo simulations. The model resulting in the highest Bayes factor included main effects for test likelihood, set size, and WMC, producing a Bayes factor of 3.56x1041 (± 0.9% sampling error) against a model including only between-participant variability. The second best model included the same main effects plus the interaction between test likelihood and WMC. Evidence in the data for the model excluding the interaction was greater than the model including this interaction by a factor of only about 1.7 (± 1.18% sampling error); this is very weak evidence for or against including the interaction between test likelihood and WMC. However, assuming that WMC actually measures individual differences in the ability to filter attention away from distractors (e.g. Vogel, McCollough, & Machizawa, 2005), we would have expected to observe this interaction in the opposite direction. The interaction between test likelihood and WMC is plotted in Figure 2, showing that 1) high-WMC individuals out-performed low-WMC individuals on both the predominant and the infrequently-tested shapes, and 2) the difference between accuracy on the predominant and infrequently-tested shapes was smaller for the high-WMC than the low-WMC individuals. Consistently with this outcome, WMC and accuracy on the infrequently-tested shapes correlated strongly ($r = 0.43$, $p < .01$). Bayes factors analyses indicated that this relationship was favored over the null by a factor of more than 30.

Accuracy on visual task									
	Full-Set			Half-Set		Ratio-Set			
						Predominant		Infrequent	
	8	4	2	8	4	8	4	8	4
High-WMC (N 22)	.70(.08)	.89(.09)	.97(.03)	.83(.10)	.96(.05)	.74(.11)	.91(.07)	.67(.12)	.86(.12)
Mid-WMC (N=23)	.67(.08)	.85(.07)	.96(.04)	.80(.10)	.94(.05)	.69(.09)	.87(.09)	.63(.11)	.82(.09)
Low-WMC (N=25)	.66(.08)	.83(.10)	.95(.06)	.77(.11)	.93(.07)	.70(.11)	.85(.12)	.55(.13)	.76(.15)

Table 1: Average proportion correct (and standard deviation) per block type, test likelihood and set size.
Note. N=70.

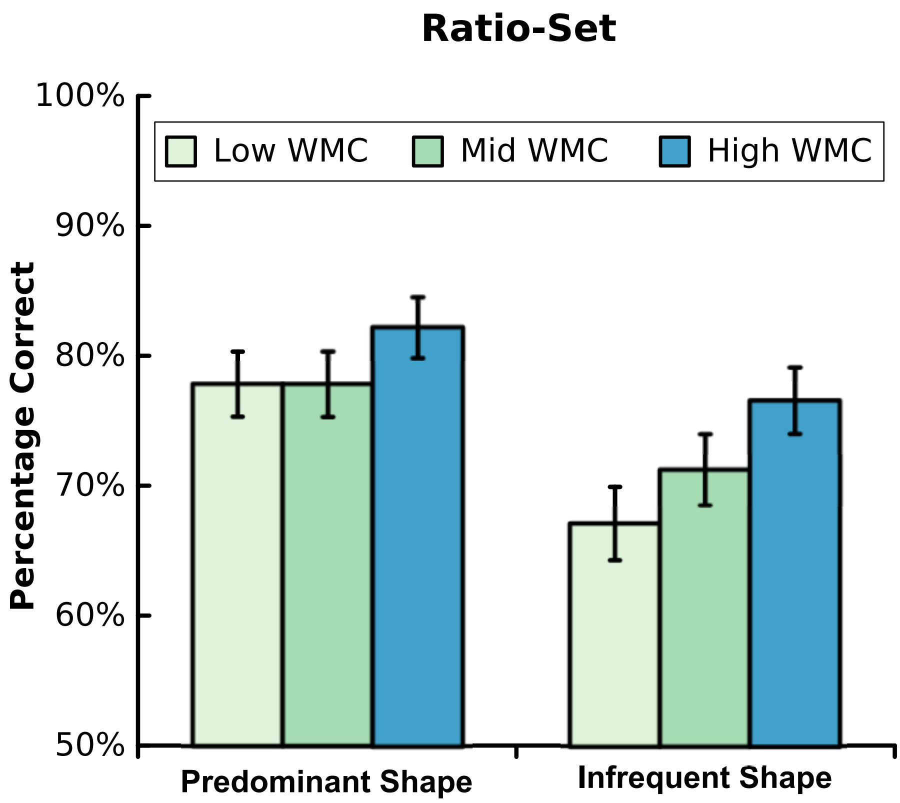


Figure 2. Average percentage correct across set-sizes in the ratio-set condition for predominant and infrequent shapes. Error bars depict standard errors of the mean. N=70.

3.3.3.2 Dwell time

To examine the preference to look at particular shapes, we computed relative proportion of dwell time toward the positions containing each kind of shape, excluding times when participants fixated on anything but shape positions. Proportions were computed separately for the memory display and retention interval. To test whether the ability to filter distractors increases visual recognition performance, we correlated the proportion

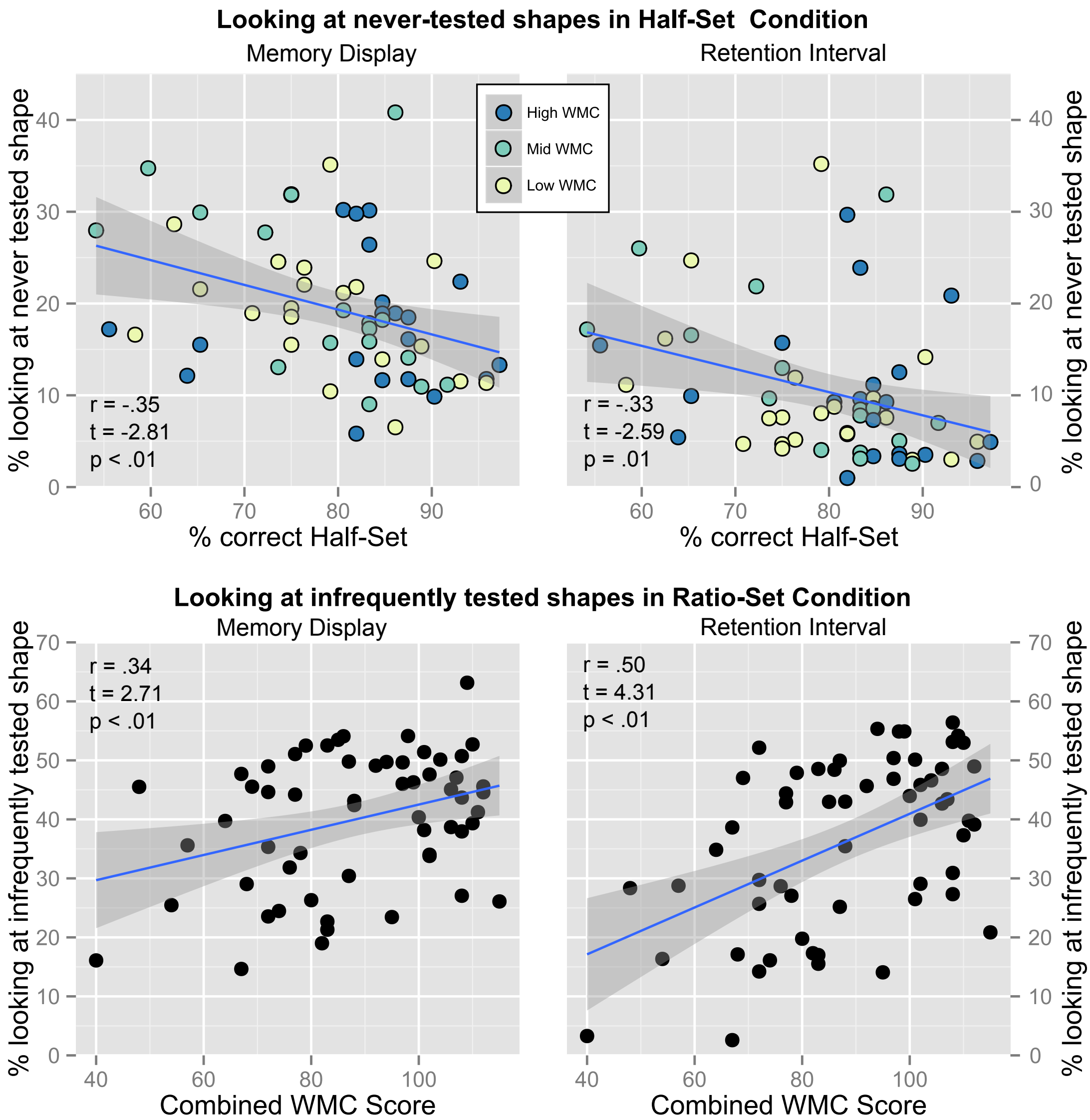


Figure 3. Correlation plots for set-size 8 trials, with best linear fit and t-based confidence interval estimation. The upper panel depicts performance in the Half-Set and looking at the never-tested shapes. Thelower panel depicts the percentage of looking at infrequently-tested shapes in the Ratio-Set and WMC scores . N=59.

Measure	1	2	3	4	5	6	7	8
Half-Set dwell percentage on irrelevant shape								
1. Memory Display								
2. Retention Interval	.37**							
Ratio-Set dwell percentage on 33.3% tested shape								
3. Memory Display	.39**	.26						
4. Retention Interval	.27*	.39**	.68**					
Performance Measures								
5. Full Set PC	-.35**	-.06	-.30*	.10				
6. Half-Set PC	-.49**	-.11	-.30*	.10	.85**			
7. Ratio-Set PC Predominant	-.50**	-.07	-.50**	-.05	.82**	.79**		
8. Ratio-Set PC Infrequent	-.10	.05	.14	.39**	.65**	.55**	.51**	
9. WMC	.27*	.28*	.27*	.50**	.20	.13	.12	.43**

Table 2: Pearson 2-tailed correlations between relative dwell times on irrelevant or infrequently tested shapes collapsed across set sizes, proportion correct (PC) per block type and WMC. Notes. * $p < .05$, ** $p < .01$. $N = 59$.

of time fixating on never-tested shapes with performance in the Half-Set block in set-size 8 trials (Figure 3, upper panels). The highest set-size was chosen to ensure that the total number of to-be-attended items was near or above capacity for all groups and thus that filtering requirements were maximal. Result patterns were similar when analyses were conducted collapsed across set-sizes (see Table 2).

In the Half-Set blocks, irrelevant stimuli were never tested and therefore could be completely ignored with no cost to performance. Consistent with the notion that filtering irrelevant in favor of relevant information increases visual change detection performance, looking less at never-tested shapes correlated with visual recognition memory performance during the memory display (see Table 2 and Figure 3, upper left panel). This is logically consistent with the results of Vogel et al. (2005): participants whose eye movements indicate a tendency to restrict looking at the irrelevant information tended to perform better. Bayes factor analysis indicates that this evidence favors some relationship between looking at the never-tested and performance by a factor of about 10; the Bayes factor that the evidence favors a specifically negative relationship is about 20. This pattern was not apparent during the retention interval (see Figure 3, upper right panel); here, the Bayes factor favored the null hypothesis by a factor of 3-4.

However, the lack of a clear pattern in the distribution of WMC groups (denoted by color) in the upper panels of Figure 3 suggests that WMC and tendency to ignore the irrelevant shapes were unrelated. Indeed, for set size 8, correlations between looking at never-tested shapes during the Half-Set blocks and WMC in both the memory display and retention interval were non-significant ($p = .19$ and $p = .22$, respectively), with Bayes factors favoring the null hypothesis by factors of at least 2.5. But when all set-sizes were combined, we found a significant positive correlation between WMC and looking at never-tested shapes during both the memory display and the retention interval, indicating that, if there is any relationship, individuals with high-WMC looked more often at these totally irrelevant stimuli. According to a directional analysis, Bayes factors against a negative correlation between WMC and looking at the irrelevant shapes exceeded 30.

To corroborate our behavioral finding that high-WMC individuals remembered infrequently tested shapes in the Ratio-Set blocks better than low-WMC individuals, we correlated the proportion of looking directed toward infrequently tested shapes with WMC (Figure 3, lower panels). In line with the notion that high-WMC individuals tried to encode more information regardless of its test likelihood, looking at infrequently tested shapes correlated positively with WMC in both the memory display and retention interval. Bayes factor analyses showed that for this relationship during the memory display, evidence only weakly favored the relationship ($BF = 1.59$). However, the Bayes factor on the data from the retention interval favored the relationship by a factor of more than 14,000.

3.3.4 Discussion

Contrary to the notion that WMC measures the ability to selectively focus attention by ignoring irrelevant information, we observed that individuals with high-WMC spent more time looking at irrelevant distractors, both in conditions where these items were never tested and in conditions where these items were infrequently tested. Most strikingly, not only was there a relationship between WMC and dwell time in the Half-Set in the opposite direction to that predicted by the strong attentional filtering hypothesis, the low-WMC individuals were clearly more prone to ignore the infrequently-tested shapes in the Ratio-Set than the high-WMC individuals. Accuracy in the Ratio-Set was best explained by a model that excluded an interaction between WMC and likelihood of tested shape, but even if we assume this interaction should be considered, it occurred in the opposite direction from what the strongest attentional filtering hypothesis would have predicted.

Analyses also showed that performance in the Half-Set was higher when filtering was more efficient during the memory display, but that WMC was, if anything, positively correlated with looking at irrelevant distractors. In the Ratio-Set, where some shapes were infrequently tested, WMC decisively predicted looking at infrequently tested shapes and correlated positively with proportion correct on infrequently tested shapes. This indicated that while we can reproduce the finding that accuracy in the visual array task correlates with filtering efficiency in the same visual array task (e.g., Fukuda & Vogel, 2009; Vogel et al., 2005), an independent measure of WMC showed the opposite relationship. This undermines the argument that WMC primarily indexes individual differences in the ability to divert attention away from irrelevant stimuli. Our results instead tend to support the ideas that individuals with high-WMC 1) can flexibly allocate their storage capacity (e.g., Colflesh & Conway, 2007), and 2) that extra capacity might spill-over to extraneous stimuli, particularly when perceptual load is lower (Lavie, Hirst, De Fockert, & Viding, 2004).

Although we typically did not find significant correlations between WMC as measured by complex span tasks and visual array task performance (Full- and Half-Set), our r values for these measures were always positive, which is consistent with previous analyses relating complex WM span to visual change detection performance (e.g. Cowan et al., 2005; Shipstead & Engle, 2013). We observed a strong correlation between WMC and accuracy only on responses to the infrequently tested shape. Our sample was smaller than some others that reported significant correlations between complex span and visual change detection tasks (e.g., Cowan et al., 2005), which could account for the non-significant relationships we observed. We consider this further in the General Discussion.

Our results, like those of Colflesh and Conway (2007), seem to suggest that high-WMC individuals can strategically divide their attention to optimize performance, while also showing that low-WMC individuals are perfectly capable of ignoring less relevant information. However, our task instructions might not have sufficiently motivated high-WMC individuals to strategically allocate attention to the predominant shapes. Possibly, high-WMC individuals believed they could remember all the stimuli in the Ratio-Set blocks and thereby optimize performance. We did not give accuracy feedback in this experiment, so the high-WMC individuals may not have realized that they were not performing near ceiling on the predominant shape probes; perhaps they did not have sufficient information to motivate a strategy of ignoring the infrequently-tested shapes. To consider this possibility, we carried out Experiment 2, in which we used rewards to motivate individuals to focus attention toward one shape over the other. The incentive was a reduction of total experiment time when individuals responded correctly. We reasoned that high-WMC individuals would then be motivated to use any attentional control advantage to perform optimally on this task. Carrying out Experiment 2 also provided the opportunity to replicate the somewhat unexpected findings of Experiment 1, namely that low-WMC individuals filter attention at least as effectively as high-capacity individuals in a visual change detection task.

3.4 Experiment 2

3.4.1 Method

3.4.1.1 Participants

Fifty-eight students from the University of Groningen (39 women, 19 men, age 18-25, M = 19.36, SD = 1.35) participated as part of their course requirements. Four participants were excluded from all analyses due to possible color blindness (i.e., 2 or more mistakes on the 6-item Ishihara test), one participant was excluded due a software malfunction, and another because of self-reported use of medicine which could affect cognitive functions. An additional 5 participants were excluded from the dwell time analyses due to erroneous calibration of the eye-tracker.

3.4.1.2 Apparatus, Stimuli and Design, and Procedure

The stimulus materials were the same as in Experiment 1. We added accuracy feedback for each trial in order to reinforce our reward instructions. Correct answers earned participants points on each trial. During each block of trials, when a participant accumulated 32,000 points, the current block ended. Thus the faster participants accumulated points, the sooner the experimental session ended for them.

Each block featured one of two within-participants probe conditions.As in Experiment 1, the shapes participants were directed to attend were counterbalanced between-participants. All trials featured eight shapes and each shape type (circle or triangle) was tested 50% of the time, depicted in Figure 4. In (A) Equal-Points blocks, participants were informed that correct answers for any shape would earn them 500 points. In (B) Ratio-Points blocks, participants were informed that the emphasized shape would earn them 900 points and the other shape 100 points.

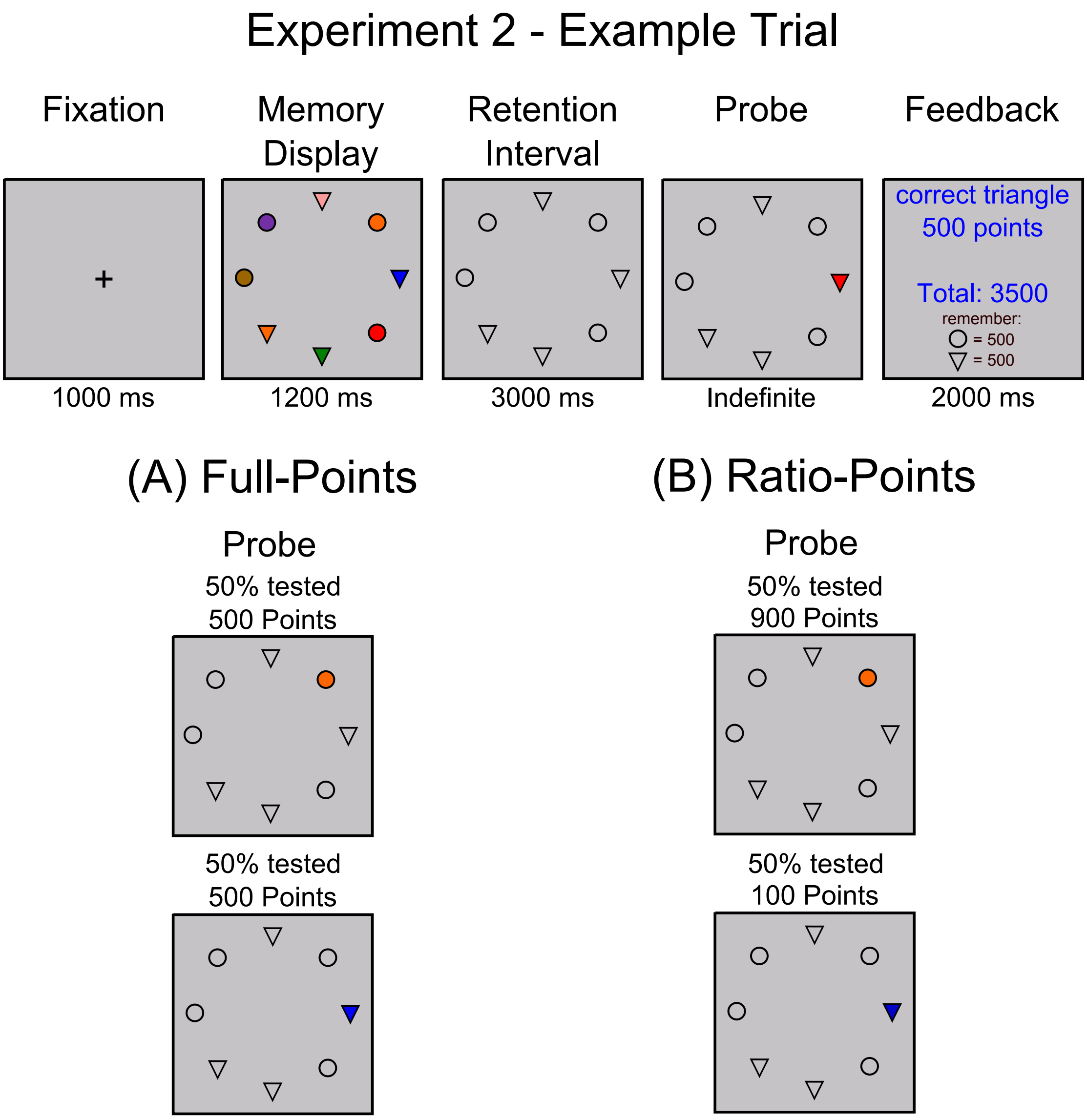


Figure 4. Schematic illustration of Experiment 2 conditions. (A) Full-Points, each correct shape awards 500 points (B) Ratio-Points, one shape awards 900 and the other 100 points. For this schematic, the predominant shape is a circle; which shape was predominant varied by participant. Changes occurred to 50% of probes in each block.

Blocks were alternated and the beginning block was counterbalanced between participants (Full-, Ratio-, Full-, Ratio-Points, or Ratio-, Full-, Ratio-, Full-Points). Between the second and third block, participants took a mandatory break of 10 minutes; breaks were also allowed at the participant's discretion between each block. The experiment, including setup and debriefing, lasted on average 94 minutes (72-147 minutes, SD = 13.72).

3.4.2 Results

3.4.2.1 Visual recognition accuracy

Proportion of correct responses was computed on the minimum number of trials needed to reach the point threshold in any block (i.e., the first 64 trials per block for each participant). To test whether WMC was related to the ability to disregard the less relevant shape in favor of the relevant shape we included block type (Ratio-Points, Equal–Points) and shape emphasis (otherwise predominant/900 Points, otherwise less relevant/ 100 Points) as within-participants factors and WMC (High, Middle and Low) as a between-participants variable. In the Equal-Points block, we expected participants to perform similarly on tests of both shapes, but in the Ratio-Points blocks, according to a strong controlled attention account of WMC, high-capacity individuals should benefit more than low-capacity individuals from the disproportionate rewards because they will be better able to allocate attention flexibly to optimize reward; this relationship would be reflected by a three-way interaction in which the difference between accuracy with 900 and 100 points is greater for the high-WMC individuals, while no groups differ much on the two tested shapes in the Equal-Points block.

Bayes factors were estimated for models including of each combination of the three possible main effects and their interactions, and calculated with 1,000,000 Monte Carlo samples. The model resulting in the highest Bayes factor included main effects for block type, shape emphasis, and an interaction between block type and shape emphasis, producing a Bayes factor of 7.21x1015 (± 0.67% sampling error) against a model including only between-participant variance. The second best model additionally included a main effect for WMC and evidence for the best model, without WMC, was greater by factor of 4.11 (± 1.08 % sampling error). The means shown in Figure 5 do not hint at any interaction between WMC and the other factors. The best model, which did not include this three-way interaction, was favored over the best model including this interaction by factor of 897 (± 2.17% sampling error). This is entirely consistent with Figure 5, which clearly suggests that all WMC groups performed much better on the high-reward than the low-reward shapes, indicating that all WMC groups were able to ignore the low-reward shape in favor of the emphasized shape to optimize performance. A two-way interaction between WMC and block type might also be considered good evidence of an effect of capacity on filtering, if it indicated that WMC effects were larger in the Ratio-Points than the Equal-Points blocks. Figure 5 does not suggest this, and the Bayes Factor against including this interaction was 26.07 (± 1.31%).

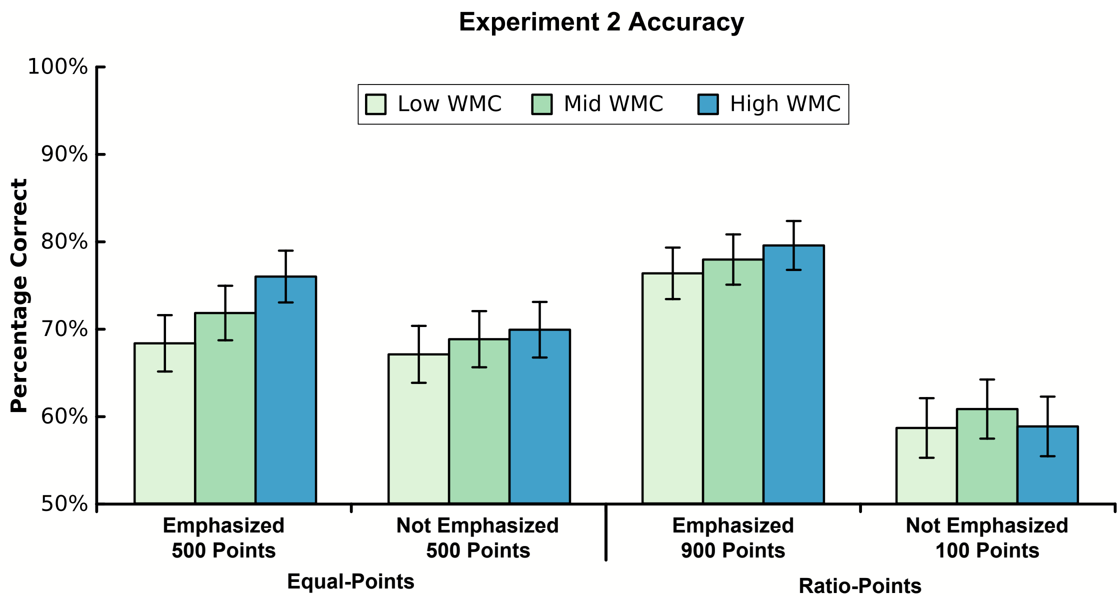


Figure 5. Average percentage correct per block type and shape emphasis. Error Bars depict standard errors of the mean. N=52.

3.4.2.2 Dwell time

To test whether the ability to filter unemphasized shapes was associated with WMC, we correlated the percentage of gazes (out of the total time spent looking at any kind of shape) directed at unemphasized shapes during the Ratio-Points blocks with WMC scores (Figure 6). Consistent with the notion that participants did not differ in their ability to filter unemphasized in favor of emphasized information, looking at unemphasized shapes did not correlate with WMC during the memory display ($r=.12$, $p=.40$) or the retention interval ($r=.16$, $p=.29$). Bayes factors favored the null by a factor of at least 5; when calculated to compare the alternative hypothesis that the relationship was negative against the null hypothesis, evidence favoring the null increased to a factor of at least 14. WMC did not correlate with any other performance or filtering measure in this experiment (Table 3). Thus in contrast to the view that efficient filtering abilities are confined to high-WMC individuals (e.g., Conway, Cowan, & Bunting, 2001; Vogel, McCollough, & Machizawa, 2005) we observed no obvious differences in strategically allocating attention across the spectrum of WMC scores, despite designing a task that should theoretically have provoked differences, if one assumes that low capacity individuals cannot control attention effectively.

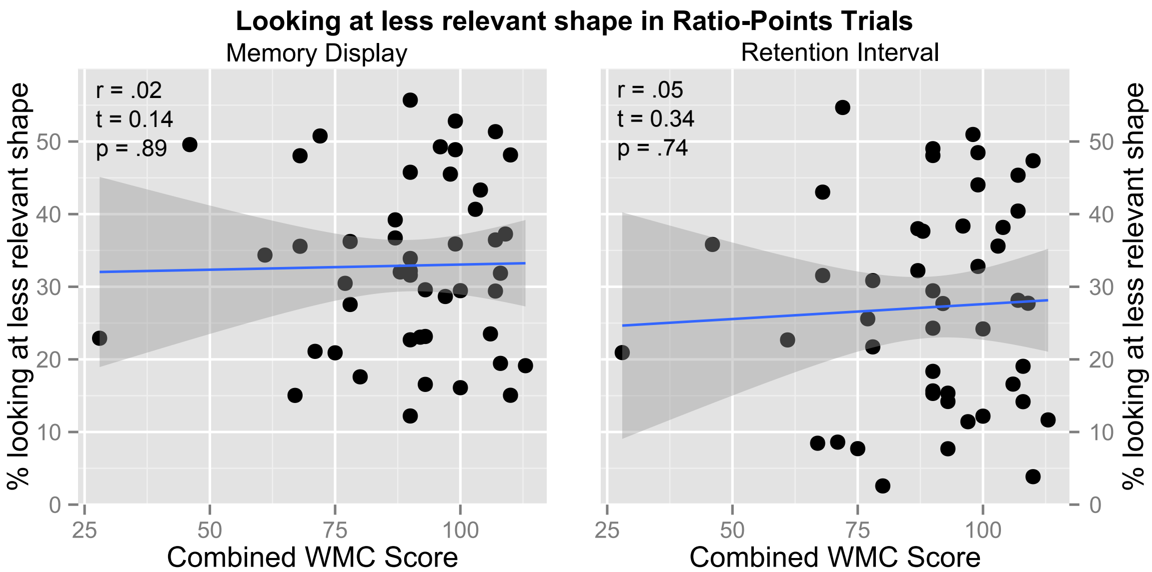


Figure 6. Correlations between percentage of time fixating on unemphasized shapes and WMC, with best linear fit and t-based confidence interval estimation, for Ratio-Points trials. N=47.

Measure	1	2	3	4	5
Ratio-Point dwell percentage on 100-Points shape					
1. Memory Display					
2. Retention Interval	.65**				
Performance Measures					
3. Equal-Points PC	-.13	-.04			
4. Ratio-Points PC 900 Points	-.62**	-.59**	.36*		
5. Ratio -Points PC 100 Points	.52**	.63**	.22	-.41**	
6. WMC	.12	.16	.05	-.08	.05

Table 3: Pearson 2-tailed correlations between relative dwell times on the unemphasized, 100-point shapes, accuracy measures and WMC.
Notes. PC = proportion correct. * = $p<.05$. ** = $p< .01$. N=47.

3.4.3 Discussion

With a strong incentive to filter less relevant information, all participants were found to selectively focus attention on the shape that gave them the highest reward. Accuracy in a visual change detection task was best explained by a model including main effects of reward block type and shape emphasis plus an interaction of these factors; we observed strong evidence against an interaction between WMC and the reward factor, especially against the three-way interaction that a strong attentional filtering account might predict. Second, dwell time analysis confirmed that the relationship between WMC and the amount of time looking at unemphasized shapes was unlikely to be negative; we thus observed no evidence that individuals with low working memory capacity paid more attention than high capacity individuals to the unemphasized shapes. Together, these results lend no support to the notion that WMC as measured by complex WM span tasks predicts individual differences in filtering efficiency in a visual recognition memory task.

3.5 General Discussion

The relationship between WMC and higher cognitive functions has previously been explained by positing differences in attentional abilities or differences in storage capacity. Both explanations can be applied to the effects of visual distractors on visual memory performance. If WMC is virtually a measure of attentional control, low-WMC individuals should be unable to filter irrelevant information as efficiently as high-WMC individuals, as observed by Vogel et al. (2005). But if storage capacity underlies WMC differences, less elegant, more complex outcomes and interpretations become necessary: high-WMC individuals may show superior filtering efficiency, or they might encode both relevant and less relevant information, perhaps in an attempt to improve performance, or simply to avoid any cost that filtering might incur.

We chose to address this using eye-tracking during a visual change detection task, comparing conditions of varying attentional filtering requirements. We used performance on complex working memory span tests collected in a prior experimental session to predict eye movements in these conditions. In Experiment 1, we operationalized attentional filtering by manipulating the proportion of trials per block that tested particular shapes. Participants were always made aware of these proportions, but were not explicitly instructed to try to remember only frequently-tested shapes. In Experiment 2, we instead manipulated the size of the reward given for correct responses to each type of shape, which we expected would make choosing to selectively attend a more attractive strategy.

Consistent with the evidence of Vogel et al., (2005), ignoring irrelevant information during stimulus encoding in visual change detection was related to visual change detection accuracy. Participants who looked less at irrelevant information performed better on tests of relevant information. However, we did not observe the same relationship between WMC as measured by complex span and looking behavior during this visual memory task. Contrary to the notion that WMC is primarily a measure of filtering efficiency, the ability to ignore irrelevant information was not confined to high-WMC individuals. We observed compelling evidence via Bayes factor analyses that individuals with low-WMC did not store items haphazardly, but selectively attended at least as well as high-WMC individuals. Reasoning that high-WMC individuals might not have realized that they could have improved their performance by selectively attending to the emphasized shapes, we carried out a second experiment using rewards to convey emphasis and providing accuracy feedback. However, we found that individuals across the spectrum of WMC scores responded similarly to the reward scheme we used in both their accuracy and looking behavior. Bayes factor analyses allowed for the quantification of the lack of differences between individuals with high, medium, and low-WMC, and produced strong evidence in support of the null hypothesis that individuals across the spectrum behaved similarly.

It has been shown previously that individuals with high-WMC can use their resources to either focus (Conway et al., 2001) or efficiently divide their attention (Colflesh & Conway, 2007). Because of this, many possible outcomes for individuals with high-WMC can be explained by the hypothesis that their control of attention is superior. However, the importance of our findings for further theorizing about relationships between attention and WMC lie in the performance of the low-capacity individuals. While it is acknowledged that high-capacity individuals may control their performance flexibly, individuals with low-WMC are expected to be far less capable of this, despite evidence suggesting that individuals from populations with low-WMC (e.g., young children or schizophrenic patients: Cowan et al., 2010; Gold et al., 2006) can ignore distracting information as well as higher-capacity populations. Our evidence confirms this equivalence when samples of low- and high-capacity individuals are drawn from the same population of healthy, young adults. In our sample, WMC scores were somewhat positively related to the tendency to look at and remember less relevant information in Experiment 1, where individuals were not explicitly instructed to attend to one type of information over another. However, in Experiment 2, in which we introduced a strong incentive to focus on the relevant information, WMC was not at all predictive of the tendency to look at and encode less relevant information. Thus in both contexts, low-capacity individuals were no more likely to attend to unemphasized information than high-WMC individuals. We think this is best explained by positing that differences in storage capacity, possibly in addition to qualified differences in attentional control, underlie WMC scores. While low-WMC individuals seemed to preserve their limited storage capacity for more relevant information irrespective of incentives, high-WMC individuals seemed to flexibly alter their strategy depending on the perceived benefit of engaging in filtering, which we think was clearer in Experiment 2.

Previous evidence for the claim that low-capacity individuals cannot efficiently filter attention has likely been inflated because measures of filtering efficiency and capacity were derived from aspects of performance on the same task. (e.g., McNab & Klingberg, 2008; Vogel et al., 2005). To measure WMC, we instead used a combined score of two popular complex working memory span tasks, for which standards of performance based on very large samples are available (Reddick et al., 2012). We think this design is more appropriate for making generalizations to broader theoretical constructs. First, our combined WMC scores included two complex span tasks, one arguably more reliant on verbal processes (i.e., operation span) and one arguably more reliant on visual processes (i.e., symmetry span); with a predictor score composed of these tasks, any relationship we observed could not be attributed only to domain-specific processes common to both tasks the WMC task and the visual recognition task. Second, these complex span tasks require participants to maintain information in the face of interference over a period of several seconds; in many of the instances we cited, this is the ability that is presumed to be lacking in low-WMC individuals (e.g., Poole & Kane, 2009). Our results in Experiment 1 are consistent with the notion that visual change detection performance might co-vary with attentional filtering at encoding, but we observed no evidence of this relationship continuing into the retention period. To the contrary, WMC scores derived from complex span tasks predicted looking behavior during both stimulus presentation and retention.

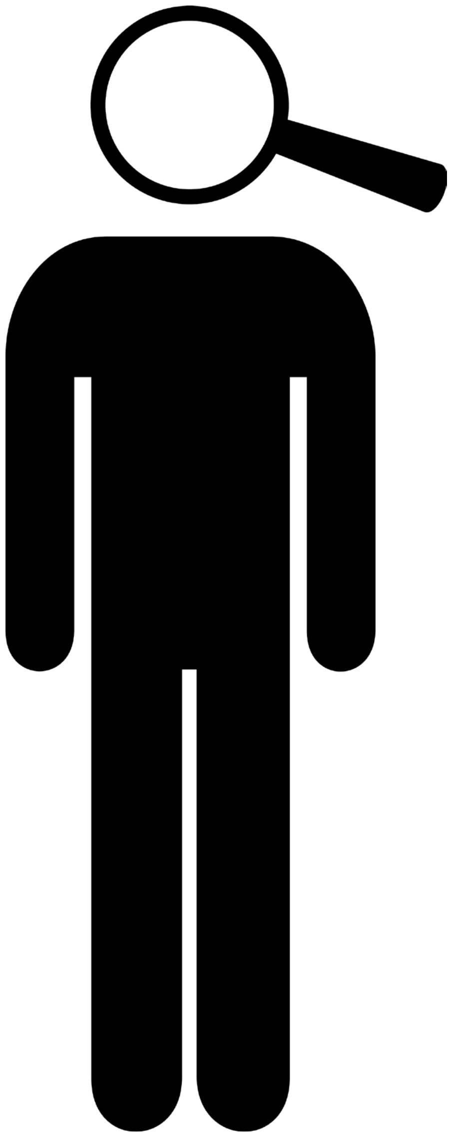
Alternative theories, such as the perceptual load hypothesis of Lavie et al. (2004), predict instead that when there is sufficient capacity (such as when perceptual load is low or WMC is high), distractors will be encoded. That previous studies have supported both the perceptual load hypothesis (e.g. Forster & Lavie, 2011) and the attentional filtering hypothesis (Vogel et al., 2005; McNab & Klingberg, 2008) suggest that boundary conditions for explaining relationships between WMC and attention are not yet sufficiently understood. One factor to be considered is the predictability of the distracting information. In our task, the completely irrelevant and unemphasized shapes were constant for each participant. Studies of auditory distraction (Beaman, 2004; Hughes et al., 2012) have shown that WMC does not correlate with effects of predictable distractors. The notion that predictability of visual distractors can decrease their ability to affect performance

(Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005) has been broached, and our results consistently suggest that low-capacity individuals can cope with these kinds of distractors. Possibly, for WMC differences in conflict resolution to emerge, distractors must be salient and unexpected (e.g. Fukuda & Vogel, 2009; Sörqvist, 2010), which contradicts the notion that low-WMC individuals helplessly store irrelevant items during visual change detection tasks.

Another factor that may predict when WMC differences in coping with distraction is the need for active maintenance of task goals. A conflict-rich context can act as a reminder of the task goal and thereby help to overcome goal maintenance deficits which seem to be prevalent in low-WMC individuals (Hutchison, 2011; Kane & Engle, 2003; McVay & Kane, 2009; Morey et al., 2012). Because the emphasized shape remained the same for participants throughout our experimental session, perhaps maintaining this information was trivial for all participants. If so, then manipulations that would necessitate retrieval of the goal could provoke WMC-based differences to emerge. Whether goal maintenance differences are themselves caused by attentional abilities or storage capacity remains open to debate. Individuals with high-WMC seem to experience lapses in attention less frequently than individuals with low-WMC (e.g. McVay & Kane, 2009); possibly, task goals are forgotten during these lapses and must be subsequently recovered. It is also plausible that high-WMC individuals use extra capacity to proactively keep task goals activated (e.g. Braver, 2012).

In some previous research, performance on visual change detection tasks and WMC as measured by complex span tasks have been strongly positively correlated (e.g. Cowan et al., 2005; Shipstead & Engle, 2013). We did not typically find significant correlations between WMC and visual recognition performance using this variant of the visual change detection paradigm. Although we consistently found positive r values, they were usually small, except for the relationship between WMC and accuracy toward unemphasized shapes in Experiment 1. Several aspects of our task differed from the standard administration, and may have affected the relationships we observed. Both our array presentations and retention intervals were longer than in a typical administration. We also mixed presentation of two types of shape, sometimes introducing an attentional filtering burden. Because Shipstead and Engle observed significant correlations between visual change detection performance and WMC even while manipulating retention intervals to durations similar to our's, we think that the novel attention allocation aspects of our task are the most obvious difference. That we found such a robust positive relationship between storing unemphasized shapes and WMC in Experiment 1 is consistent with the idea that in our paradigm, storing these "extra" items really distinguished high and low-capacity individuals. This suggests that as it is typically administered, visual change detection correlates with complex span because it effectively measures WM storage capacity (Cowan et al., 2005).

In conclusion, by showing that low-WMC individuals are at least as capable as high-capacity individuals of selectively attending based on test likelihood or reward, we cast considerable doubt on the hypothesis that WMC differences emerge because low-capacity individuals cannot prevent themselves from attending irrelevant or unimportant stimuli. This research will help theorists determine appropriate boundary conditions to set upon theoretical relationships between attention and working memory capacity, which is crucial to enabling prediction of how distraction effects and WMC are related.



CHAPTER 4 FOCUSED SEARCH

A version of this chapter has been published as Mall, J. T., & Morey, C. C. (2013). High Working Memory Capacity Predicts Less Retrieval Induced Forgetting. PloS one, 8(1), e52806 and can be accessed online http://dx.plos.org/10.1371/journal.pone.0052806

4.1 Abstract

Background: Working Memory Capacity (WMC) is thought to be related to executive control and focused memory search abilities. These two hypotheses make contrasting predictions regarding the effects of retrieval on forgetting. Executive control during memory retrieval is believed to lead to retrieval induced forgetting (RIFO) because inhibition of competing memory traces during retrieval renders them temporarily less accessible. According to this suggestion, superior executive control should increase RIFO. Alternatively, superior focused search abilities could diminish RIFO, because delimiting the search set reduces the amount of competition between traces and thus the need for inhibition. Some evidence suggests that high-WMC is related to more RIFO, which is inconsistent with the focused search hypothesis.

Methodology/Principal Findings: Using the RIFO paradigm, we created distinct and overlapping categories to manipulate the amount of competition between them. This overlap increased competition between some categories while exclusive use of weak exemplars ensured negligible effects of output interference and integration. Low-WMC individuals exhibited RIFO within and between overlapping categories, indicating the effect of resolving competition during retrieval. High-WMC individuals only exhibited between-category RIFO, suggesting they experienced reduced competition resolution demands. Low-WMC Individuals exhibited the strongest RIFO and no retrieval benefits when interference resolution demands were high.

Conclusions/Significance: Our findings qualify the inhibitory explanation for RIFO by incorporating the focused search hypothesis for materials that are likely to pose extraordinary challenges at retrieval. The results highlight the importance of considering individual differences in retrieval-induced effects and qualify existing models of these effects.

4.2 Introduction

Retrieving particular information from memory, while fundamentally important for everyday tasks, also seems to impair memory for related but unretrieved information. This phenomenon, called retrieval-induced forgetting (RIFO), might give us important insights into the way our memory system works. RIFO is believed to be caused by inhibitory processes during retrieval, which diminish accessibility of related items. RIFO has been observed in many contexts, including semantic relations (Anderson, Bjork, & Bjork, 1994; Bäuml & Hartinger, 2002) episodic contexts (Ciranni & Shimamura, 1999), category recognition (Spitzer & Bäuml, 2009), propositional material (Anderson & Bell, 2001) and within a foreign language acquisition context (Levy & Anderson, 2008).

The retrieval practice paradigm has three phases. First, the study phase in which a full set of associations (e.g. Weapon - Machete) are presented and learned. Second, the participants engage in a retrieval practice phase in which some words from certain categories receive retrieval practice (RP+) while other items from the same category (RP-) and items from the remaining categories (NRP) receive no retrieval practice. Finally, in the retrieval phase memory for all associations is tested. RIFO effects are found using a variety of recall and recognition methods, including retrieval via category cues (e.g. Bird) (Bäuml & Aslan, 2004), stem completion, and cue-independent tests like item recognition (Aslan & Bäuml, 2010; Hicks & Starns, 2004) (but see (Butler, Williams, Zacks, & Maki, 2001) for criticism on these methods).

The RIFO effect is believed to be due to inhibitory executive-control processes that occur during the retrieval practice phase (Anderson, 2003), when resolving interference of competing memory representations is necessary to retrieve the correct item. Support for the inhibition interpretation comes from the observation that unpracticed targets closely related to the practiced items seem to be less accessible after retrieval practice even when probed with a new, unstudied cue (Anderson, Bjork, & Bjork, 2000; Saunders & MacLeod, 2006). Finding RIFO even with independent cues supports the notion that not only the cue-target association has been weakened, but the concept of the target itself has been temporarily inhibited. RIFO can occur even when practiced items were not successfully retrieved during the retrieval practice phase. This meant that retrieval cues, impossible to resolve, still lead to worse performance on related compared to non-practiced items (Storm, Bjork, Bjork, & Nestojko, 2006). The contribution of inhibition was further demonstrated in a recent study in which the necessity of resolving interference of competing memory representations was directly manipulated. Participants were exposed to orthographically similar words during a vowel counting task. Half of them were then presented with a word completion task that allowed only one of two similar words as the right answer. A later naming task revealed that the group who had to resolve interference during the word completion took longer to read the competitor words aloud (Healey, Campbell, Hasher, & Ossher, 2010). Together, this evidence supports the notion that resolving interference through inhibition affects later retrieval, decreasing the likelihood of retrieving the previously inhibited concepts.

However, the inhibitory explanation for RIFO is not beyond criticism. The inhibition explanation predicts that repeated retrieval should produce additive inhibition of unrelated items, resulting in stronger RIFO, the more often an item is retrieved. Jakab and Raaijmakers (Jakab & Raaijmakers, 2009) manipulated item strength by changing the amount of retrieval practice an item received, but found that increasing item strength did not produce stronger RIFO effects. Others have failed to replicate findings of RIFO with independent cues (Anderson et al., 2000), which could mean that the memory deficit is linked to the specific retrieval cue and that blocking may be causing RIFO. Blocking occurs when the previously retrieved items are remembered in response to the retrieval cue instead of the unpracticed target items. The blocking hypothesis assumes output interference at test, but when output interference is controlled for by using recognition (Hicks & Starns, 2004) or independent probe tests (Anderson & Spellman, 1995; Saunders & MacLeod, 2006), RIFO is still observed (but see (Perfect et al., 2004) who doubt the cue-independent nature of RIFO). Lastly, populations believed to have low inhibitory executive control still exhibit RIFO; young children (Ford, Sam, & Rina, 2004; Zellner & Bäuml, 2005), people with schizophrenia (Racsmány et al., 2008) and people with Alzheimer's disease (Moulin et al., 2002).

It has been suggested that the absence of RIFO effects may be accounted for by factors influencing memory consolidation. For example, in some studies (Bäuml & Hartinger, 2002; Butler et al., 2001) the absence of RIFO effects can be explained by integration of practiced and unpracticed items during repeated retrieval. Integrating happens when two or more items are associated with each other, which aids the retrieval of either, since items become retrieval cues for each other (Anderson & McCulloch, 1999). If integration between two targets has occurred, then practicing one target during the retrieval practice phase might still aid retrieval of the unpracticed target. Integration is more likely when participants rehearse items together, try to form meaningful interrelations (Anderson & McCulloch, 1999) or when target and competitor items are strongly associated (Bäuml & Hartinger, 2002; Butler et al., 2001; Goodmon & Anderson, 2011). Stimuli designed to have few associative connections between target and competitor items tend to produce RIFO effects (Anderson et al., 1994; Anderson, Green, & McCulloch, 2000; Anderson & McCulloch, 1999; Bäuml & Hartinger, 2002). Anderson and Spellman (Anderson & Spellman, 1995) explain the integration effect with a feature suppression model. While greater feature overlap may lead to more competition between items, successful retrieval strengthens shared features, offsetting the effects of inhibition. Unique features of competing items on the other hand are inhibited, decreasing the likelihood that the item will be retrieved at a later point. The feature suppression model therefore predicts RIFO when target and competitors are moderately similar, while dissimilar, non-overlapping items are not inhibited. In summary, item characteristics and their inter-relations need to be controlled for to achieve convincing RIFO effects.

More evidence against the alternative blocking explanation comes from neurological studies examining the role of prefrontal activation in RIFO. In an fMRI study, the amount of RIFO was predicted by activity during the test phase in an area associated with the retrieval of weak memories, the left anterior VLPFC (Wimber et al., 2008). Critically, no activation was found in the mid-VLPFC, commonly associated with resolving interference (Badre & Wagner, 2007). Activity in the mid-VLPFC would have indicated that highly activated representations block access to the related representations. Finding left anterior VLPFC activity suggests that inhibitory control processes have weakened related but unretrieved memory representations during the retrieval practice phase.

In the present study we look at executive control contributions from an individual differences perspective. Previous work indicates that executive control abilities are directly related to working memory capacity (WMC). WMC is widely believed to be not merely a measure of storage capacity (Vogel, McCollough, & Machizawa, 2005) but also reflects the ability to control attention or suppress irrelevant information (Conway, Cowan, & Bunting, 2001; Kane, Bleckley, Conway, & Engle, 2001; Redick, Heitz, & Engle, 2007). WMC has also been associated with prefrontal activation (Cohen et al., 1997; Wagner, Maril, Bjork, & Schacter, 2001), particularly areas related to executive control, suggesting that the neural networks supporting executive control are more active in high-WMC individuals.

With regards to executive control and RIFO, the evidence appears to be mixed. In line with the notion that executive control processes are applied during retrieval practice, RIFO disappears when a secondary task taxing executive control is introduced during retrieval practice (Román, Soriano, Gómez-Ariza, & Bajo, 2009). Additionally, Bäuml and Hanslmayer (Aslan & Bäuml, 2010) used operation span scores as a measure of WMC and correlated it with RIFO effects derived from an item recognition task. The positive correlation between WMC and RIFO scores suggested that high-WMC individuals applied more executive inhibitory control during retrieval practice, leading to more forgetting of related items. Groome, Thorne, Grant and Pipilis, (Groome, Thorne, Grant, & Pipilis, 2008) on the other hand found no relationship between executive control and RIFO. They tested people with a high or low capability to inhibit intrusive thoughts, an ability strongly linked with WMC (Brewin & Beaton, 2002; Brewin & Smart, 2005), and found no RIFO difference between groups. Together, the evidence suggests that high-WMC individuals are better able to exert executive control but such a difference does not necessarily translate into stronger RIFO effects.

A possible explanation for the current discrepancies might be found when considering that inhibition comprises different sub-processes. Latent variable analysis has shown that inhibition within memory seems to be dissociable from the inhibition of response tendencies such as moving the eyes to fixate a visual target (Friedman & Miyake, 2004). Controlled search as related to resistance to proactive inhibition thus seems unrelated to resistance to distractor interference (Friedman & Miyake, 2004). To illustrate, in cued recall, low-WMC individuals recall fewer items, make more errors, and have longer recall latencies than high-WMC individuals (Unsworth, 2009). These findings are consistent with the idea that individuals with low-WMC search a bigger set of items retrieved from long term memory (LTM) than their high-WMC counterparts. These differences could be explained by the specificity of retrieval cues (Unsworth & Engle, 2007a). During memory search, retrieval cues are used to discriminate between relevant and irrelevant information to reduce the amount of competition at retrieval. Unsworth and Engle (Unsworth & Engle, 2007a, 2007b) argue that when searching for a memory trace, high-WMC individuals delimit their search set by using more specific retrieval cues, while low-WMC individuals use unspecific cues and thus commit more irrelevant items into their search set. Using cues less efficiently also means that performance on earlier trials should be comparable for both groups, but the accumulation of items in the search set disproportionally harms low group individuals who do not use retrieval cues as efficiently to limit entry to the search set as individuals in the high group may. This effect has been shown with the Brown Peterson task, where performance on the first trial is equal between low and high-WMC but diminishes more sharply for low-WMC individuals (Kane & Engle, 2000). Low-WMC individuals also seem to build up proactive interference faster than high-WMC individuals (Lustig, May, & Hasher, 2001), whereas release from PI is similar for both groups (Bunting, 2006) .

In this study, we aim to examine the contribution of controlled search and executive control on RIFO effects. Expanding on the findings of Bäuml and Hanslmayer (Aslan & Bäuml, 2010), who show a positive relationship between WMC and RIFO, we argue that controlled search for high-WMC individuals would prevent competition between items to arise and thereby diminish the need for inhibition. While Bäuml and Hanslmayer (Aslan & Bäuml, 2010) used item recognition and a one-minute consolidation interval between retrieval practice and recall, we test the relationship of WMC and RIFO with the more commonly used paradigm developed by Anderson et al. (Anderson et al., 1994). To avoid output interference, we use items with low taxonomic frequencies. Items low with taxonomic frequency, or weak items, are less likely to block access to related but unpracticed items (Bäuml, 1998) but are also less likely to be falsely retrieved during retrieval practice.

Since RIFO relies on competition during retrieval practice, weak items are less susceptible to RIFO (Anderson et al., 1994). To create competition while using weak exemplars, we created categories with overlapping or distinct features. For the overlapping categories (e.g. Sharp and Weapon), items shared features, (i.e. both categories contained sharp weapons) whereas distinct items did not conceivably overlap (e.g. Hobby or Cold). Each category had an equal number of items to prevent cue-overload. Although items in overlapping categories share features, they have different, specific retrieval cues (e.g., Weapon or Sharp).

We believe that Anderson and Spellman's (Anderson & Spellman, 1995) feature suppression model can be qualified by the controlled search hypothesis of Unsworth and Engle (Unsworth & Engle, 2007a) in the sense that only features of items that are part of the search set are suppressed during retrieval practice. Thus, if cues are used effectively during retrieval practice, competition between items from overlapping categories (e.g. Sharp and Weapon) is less likely and RIFO effects should be small or absent. If cues are used less effectively causing items from the overlapping (but irrelevant) category to be considered in the search set, RIFO effects should be observed. High-WMC individuals may use specific retrieval cues (e.g. remembering the length of a word) to limit their search to a small, appropriate set of candidates, while low-WMC individuals may use unspecific retrieval cues (e.g. whether the item was a sharp weapon), resulting in a larger set of candidates to choose from, requiring more interference resolution. If high-WMC individuals differ from low-WMC capacity individual because of their effective use of retrieval cues, they should show little to no RIFO, unlike previous reports have suggested (Aslan & Bäuml, 2010).

Our results confirmed that low-WMC individuals exhibited RIFO within and between overlapping categories, suggesting that they were unable to delimit their search set effectively. High-WMC individuals only exhibited between-category RIFO which suggests that they suffered less from interference. Only high-WMC individuals exhibited retrieval-induced facilitation effects for overlapping items, which again indicated their ability to search long-term memory more effectively. Both findings support the focused search hypothesis, and suggest that it should continue to be incorporated into broader discussions of attentional control and memory.

4.3 Materials and Methods

4.3.1 Ethics Statement

The study was approved by the local ethics committee ("Ethische Commissie Psychologie") and participants gave written informed consent before the study began.

4.3.2 Participants

The sample consisted of 125 students from the University of Groningen (95 women, 30 men, age ranged 18-43 years, M = 19.88 years, SD=2.65) who participated as part of their course requirements. Participants were fluent Dutch-speakers, following a university curriculum taught entirely in Dutch. Participants were tested in a room with multiple individual cubicles. The experiment was run in groups of up to 8 participants at a time. E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) was used to run the experiment.

4.3.3 Working Memory span tasks

Participants completed computerized versions of the operation (Unsworth, Heitz, Schrock, & Engle, 2005) and symmetry span task (Unsworth, Redick, Heitz, Broadway, & Engle, 2009) in a prior session to determine their working memory capacity. In operation span, participants were asked to remember serially-presented consonants, interleaved with a secondary task, judging the accuracy of math equations. For each trial, different letters (F, H, J, K, L, N, P, Q, R, S, T, and Y) and equations were presented 3-7 times before participants recalled the letters in order. In symmetry span, participants were instructed to remember serially-presented locations of red squares in a 4x4 matrix interleaved with a secondary task, judging whether a block pattern was vertically symmetrical. In each trial different locations and block patterns were presented 2-5 times, before participants recalled the locations on the matrix in order. An 85% correct criterion for performance on the secondary task (math equations and symmetry judgment) was required to take part in the following experiment. Performance was measured using the count of correct trials for a maximum score of 75 for the operation Span and 42 for the symmetry span (Unsworth et al., 2005, 2009). Both scores were added to create a WMC composite score. Low and high groups were created using a thirtile split of the composite score with scores below 61 or above 80, respectively.

4.3.4 Retrieval practice task

4.3.4.1 Design

Two factors were manipulated within subjects: Retrieval-Status and Set-Type. Retrieval-Status had three levels, items that received retrieval practice (RP+), related but unpracticed items (RP-) and items from categories that received no retrieval practice (NRP). Set-Type had two levels, Distinct Set (DS) and Overlap Set (OS). To ensure that Retrieval-Status was evenly distributed between the items, a random selection of three items per category was associated equally often with each Retrieval-Status. Counterbalancing of items resulted in eight different lists, which were randomly assigned to participants.

4.3.4.2 Word stimuli.

Ten categories from Dutch category norms [unpublished data, see appendix] were selected. Eight categories (food, cold, hobby, soft, sharp, weapon, flying, animal) were used as experimental categories and two categories (loud, swim) as fillers. Two pairs of related categories (sharp, weapons and flying, animals) formed the overlap set (OS) and the four remaining experimental categories formed the distinct set (DS). Distinct set categories were created with words that could not be confused as being members of another category, (e.g. words like “ice cream” that could fit into Food or Cold and were excluded). The category names were unambiguous, single words, with lengths between 3 and 6 letters. Words had a low average taxonomic frequency ($M \pm SD = 62 \pm 31.38$, Median=60.5, range=16-136). Items were chosen with a length between three and eight letters ($M \pm SD = 5.06 \pm 1.28$), and had between one and three syllables. No two items within a category or between the related categories began with the same initial letter. See Appendix, for the complete word list.

4.3.4.3 Study lists

For each study list, 12 filler and 48 experimental category-item pairs were constructed. Similarly to previous experiments (e.g. (Anderson et al., 1994)), six experimental blocks were created to ensure that items assigned to various retrieval statuses were fairly dispersed across the study period. In each block, one item was randomly selected from each of the eight categories. To ensure even presentation of eventual RP+ and RP- items, the first block featured an RP+ item from one half of the to-be-practiced categories and an RP- item from the other half (see (Jakab & Raaijmakers, 2009)). Subsequent blocks presented RP+ and RP- items in an alternating order. Study lists began with the two filler categories. The study lists were presented once.

4.3.4.4 Retrieval-practice lists

Category-target associations were practiced by retrieving a specific item given a category-plus-one-letter-stem. The practiced items, three per category, came from two of the distinct sets, two of the overlap sets and from each of the two filler categories. Each category-item pair was practiced one time resulting in 18 exemplars per list. To maximize the impact of retrieval practice, RP+ items were presented in an expanding schedule with interleaved tests of filler items, ordered to produce an expanding sequence of inter-test intervals (see (Anderson et al., 1994)). There were on average 4.7 items presented between two exemplars from the same category. No two category members were presented adjacently.

4.3.4.5 Test lists

In the test list a category name and the initial letter of the tested item was provided. Cued recall began with a filler category followed by the eight experimental categories. Half of the experimental categories began with a practiced category and the other half with a non-practiced category. Practiced and unpractised categories were subsequently presented in an alternating order. Within a list, half of the practiced categories began with randomly selected RP+ items, the other half began with randomly selected non-practiced RP- items. In total, 54 category-item pairs were tested; the second filler category was not tested.

4.3.4.6 Procedure

The procedure followed the retrieval practice paradigm developed by Anderson et al. (Anderson et al., 1994). The experiment consisted of five phases: Study, retrieval practice, filler task, cued recall and the free recall. In the study phase, participants were instructed to study category-exemplar combinations and to remember the exemplars by relating them to their category. Each trial consisted of a central fixation point for 1000 ms, followed by a blank screen for 500 ms, followed by one of the "category – exemplar" combinations for 5 s, followed by another blank screen for 500 ms, before the next trial began.

In the retrieval practice phase, participants were instructed to complete category-plus-one-letter-stem cues for the RP+ and filler items, with exemplars that were learned during the study phase. A trial began with a fixation point for 1000 ms, followed by a blank screen for 500 ms, followed by a category-plus-one-letter stem cue (e.g. Hobby – R_____) with an empty square underneath. Participants entered their response and after they confirmed by pressing Enter, the correct answer was shown for 2 s (e.g. Hobby – Rugby), followed by another blank screen for 500 ms, before the next trial began.

Next participants completed a filler task, a 25-minute visual change detection task. This was meant to allow time for consolidation of the category-exemplar pairs into long-term memory, while preventing active rehearsal of these materials. In the cued recall phase, participants were instructed to complete category-plus-one-letter-stem cues of all items, with exemplars learned during the study phase. Each trial began with a fixation point for 1000 ms, followed by a blank screen for 500 ms, and finally a category-plus-one-letter-stem cue with an empty square underneath. Participants were asked to respond within 7s and press enter to get to the next cue or press enter immediately to indicate that they do not know the correct answer. The whole experimental session lasted about 60 minutes.

4.4 Results

All statistical analyses employed two-tailed tests. Post-hoc tests were Bonferroni-corrected and an alpha level of .05 was used throughout the analysis.

4.4.1 Retrieval Practice Phase

For the first retrieval phase, the percentage correct recall for RP+ items from the two Set-Types was calculated per subject. We used a two (Set-Type) by three (WMC Bin) repeated measures analysis of variance (ANOVA) with a Greenhouse-Geisser correction. Set-Type (OS RP+, DS RP+) was entered as a within-subject factor and WMC bin (1-3) as a between-subject factor. We found that recall was reliably higher for distinct ($M = 45.5\%$) than for overlap items ($M = 34.1\%$), $F(1,122) = 22.23$, $MSE = .81$, $\eta 2p = .15$, $p < .001$. A reliable interaction was found between Set-Type and WMC, $F(2,122) = 6.67$, $MSE = .24$, $\eta 2p = .10$, $p = .002$. Post-hoc comparisons indicated that for lowest WMC individuals, retrieval of overlapping RP+ items was worse than for distinct RP+ items ($M = 28.6\%$ and 51.2%, $p < .0001$) whereas for highest WMC individuals, retrieval was comparable ($M = 44.0\%$ and 43.2%, $p = .84$). No other effects or interactions were found ($ps = .10$-$.62$).

Retrieval success rate was lower than the 74% success rate reported for weak category exemplars in previous research (Anderson et al., 1994). This difference was expected and can be accounted for by the use of category-plus-one-letter-stem cues instead of category-plus-two-letters-stem, the single presentation during retrieval practice and the items' low taxonomic frequency (rank order $M = 62$ compared to $M = 33$ according to (Battig & Montague, 1969) in (Anderson et al., 1994)). In summary, while overall retrieval success was moderate, low-WMC individuals showed worse retrieval of overlapping RP+ items than high-WMC individuals.

4.4.2 Reaction times during retrieval practice

A repeated measures ANOVA with Set-Type as the within-subjects variable and WMC as the between-subjects variable yielded no reliable effect or interaction ($ps = .45$-$.79$) on mean response times, providing no evidence that speed of successful retrieval during practice differed between groups or Set-Types.

4.4.3 Cued Recall Test

To investigate the effects of Retrieval-Status and Set-Type on cued recall, recall rates were computed for RP+, RP- and NRP items within the distinct and overlap set in all lists. A repeated measures ANOVA was conducted with Retrieval-Status (RP+, RP- and NRP) and Set-Type as within-subjects factors and WMC (thirtiles 1 - 3) as a between-subjects factor. For Retrieval-Status we found a main effect, $F(2,244) = 231.25$, $MSE = 6.24$, $\eta 2p = .60$, $p < .001$. Post-hoc comparisons indicated improved recall of RP+ (56.2%) and decreased recall of RP- ($M = 27.5\%$), compared to NRP items ($M = 32.1\%$), $p < .001$. A main effect was found for Set-Type, $F(1,122) = 146.82$, $MSE = 4.01$, $\eta 2p = .55$, $p < .001$). Post-hoc comparisons indicated that recall for distinct items was reliably higher ($M = 46.0\%$) than in the OS ($M = 31.2\%$), $p < .001$. Set-Type and Retrieval-Status interacted with each other $F(2,244) = 8.30$, $MSE = 1.69$, $\eta 2p = .06$, $p = .001$). We have described this interaction in more detail in the next section.

Working Memory Capacity interacted with Retrieval-Status, $F(4,244) = 3.37$, $MSE = .10$, $\eta 2p = .05$, $p = .012$ and Set-Type, $F(2,122) = 6.14$, $MSE = .17$, $\eta 2p = .09$, $p = .003$). With regard to Retrieval-Status, post-hoc comparisons indicated that NRP performance was comparable between the three WMC groups ($ps = .68$-1) but high-WMC individuals recalled more RP- items than those with low-WMC ($p = .034$). With regards to Set-Type, recall of distinct items was comparable for all WMC groups ($p \approx 1$) but high-WMC individuals recalled significantly more OS items ($M = 37.3\%$) compared to both the middle ($M = 29.0\%$, $p = .018$) and low group ($M = 7.3\%$, $p = .004$). There were no other main effects or interactions of WMC with any other factor ($ps = .067$-1).

4.4.4 Retrieval induced forgetting and facilitation

To investigate retrieval-induced effects, we used the recall rate of distinct NRP items as the baseline to calculate RIFO and RIFA because it was least affected by interference. For RIFO, we were interested in two separate comparisons to differentiate between within- and between-category effects. Within-category effects, between RP+ and RP- items from the same category were quantified by comparing recall of distinct NRP to the recall of RP- items in both distinct and overlapping sets.. The between-category effect, amongst practiced overlapping categories and related overlapping NRP items, was quantified by comparing performance on distinct NRP and overlapping NRP items. For RIFA effects, distinct NRP was compared to distinct RP+ and overlapping RP+ performance. Figure 1 A and B illustrate the RIFO and RIFA comparisons.

A repeated measures analysis of variance (ANOVA) was conducted with Retrieval-Status (DS NRP, DS RP-, DS RP+, OS NRP, OS RP- and OS RP+) as the within-subject factor and WMC (low, high) as the between subjects factor. A main effect of Retrieval-Status ($F(5,405) = 87.32$, $MSE = 3.00$, $\eta 2p = .52$, $p < .001$) was observed. Post-hoc comparisons indicated RIFO only for overlapping items, as performance on distinct NRP items was higher than for overlapping NRP and RP- items ($p < .001$). Post-hoc comparisons also indicated RIFA, as distinct RP+ and overlapping RP+ recall was higher than for distinct NRP items ($p < .01$). This effect was qualified by an interaction between Retrieval-Status and WMC ($F(5,405) = 4.01$, $MSE = .16$, $\eta 2p = .05$, $p = .001$). A post-hoc comparison indicated that contrasted with distinct NRP recall, low-WMC individuals had lower recall for overlapping NRP and RP- items, while distinct RP+ recall was higher ($ps < .001$). The same contrast revealed that high-WMC individuals had lower recall of overlapping NRP items, while recall of both distinct RP+ and overlapping RP+ items was higher ($ps < .01$). See Table 1 for means and Figure 1 for these differences.

Lower performance for overlapping items may partly have been the result of proactive interference. Even though there were always six items per category, participants might have combined the category cue (e.g. sharp or weapon) to form a universal cue (e.g. sharp weapons) which would have led to cue overload and a general decrease of recall for overlapping items; therefore we repeated the analysis only within the OS where interference would have been equal for all items. A repeated measures ANOVA was conducted with Retrieval-Status (OS NRP, OS RP-) as the within-subject factor and WMC (low, high) as the between subjects factor. No main effect for Retrieval-Status was found ($F(1,81) = 1.25$, $MSE = .03$ $\eta 2p = .02$, $p = .268$) but the Retrieval-Status x WMC interaction approached significance ($F(1,81) = 3.78$, $MSE = .08$ $\eta 2p = .04$, $p = .055$), indicating a trend toward the result observed in the full, more powerful analysis. A post-hoc comparison indicated that for overlapping items, low-WMC individuals' performance on RP- items was significantly lower than for NRP items ($p = .03$) whereas high-WMC individuals showed no difference ($p = .57$).

To summarize, we found no RIFO for distinct items. For overlapping items, both low and high-WMC individuals exhibited between-category RIFO, while only low-WMC individuals exhibited significant within-category RIFO. While proactive interference might have played a role, the pattern of results is consistent within the set in which proactive interference would have been present for all items. RIFA was observed in both groups for distinct items while only high-WMC individuals showed better recall of practiced overlapping items.

	Distinct Set			Overlap Set		
Group	**NRP**	**RP-**	**RP+**	**NRP**	**RP-**	**RP+**
Low-WMC (N=43)	35.85(.03)	29.07(.04)	73.26(.04)	23.64(.02)	16.67(.03)	41.86(.04)
High-WMC (N=40)	38.34(.03)	35.84(.03)	64.99(.03)	27.3(.02)	29.18(.03)	55.42(.03)

Table 1. Percentage correctly recalled items per condition with standard deviations.

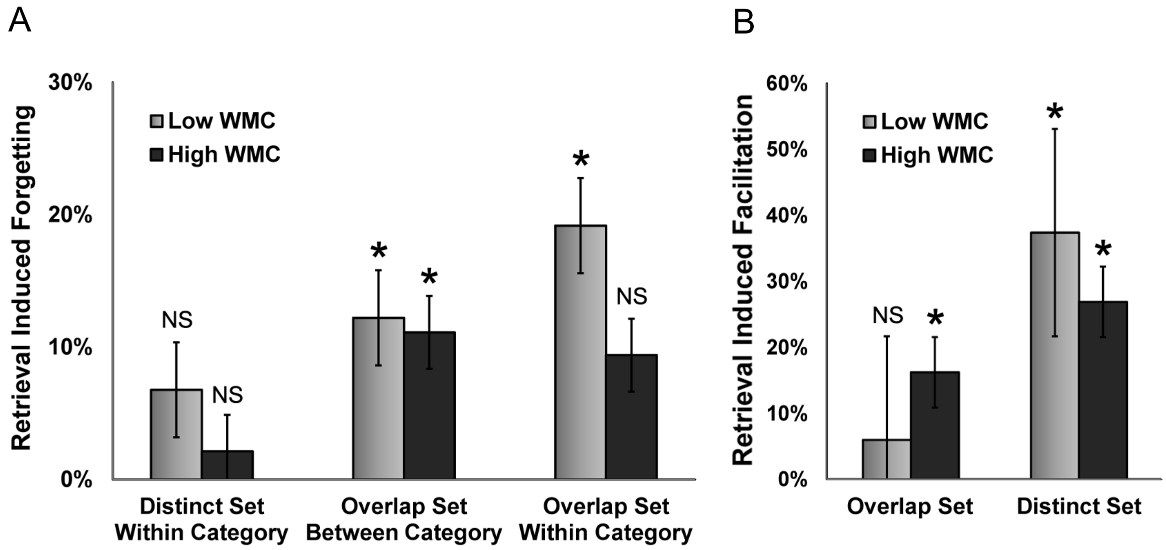


Figure 1. Retrieval induced effects for high and low working memory capacity individuals.

(A) RIFO scores were calculated by subtracting average performance of DS RP-, OS NRP and OS RP- from DS NRP performance. (B) RIFA scores were calculated by subtracting average performance of DS NRP from OS RP+ and DS RP+ performance. The * and NS show the results of the comparison between DS NRP and respective retrieval status performance. * means the difference is significant, whereas NS means the difference is nonsignificant $p < .05$. In the overlap set, within category, low-WMC individuals show RIFO but no RIFA and high-WMC individuals show no RIFO but intact RIFA.

4.4.5 Correlation Analysis

To test the relation of WMC and RIFO, we calculated the three RIFO and two RIFA scores per subject and correlated them with the WMC composite score. The correlations are reported in Table 2. In line with our prediction and counter to the earlier findings by Bäuml and Hanslmayer (Aslan & Bäuml, 2010), the WMC composite score correlated negatively with the amount of within-category RIFO in the OS. We also found negative correlations between RIFA and RIFO effects, suggesting that individuals who benefitted from retrieval practice failed to report related items.

Measure	1	2	3	4	5
1. Composite WMC Score					
2. Distinct Set Within-Category RIFO	-.05				
3. Overlap Set Between-Category RIFO	-.11	**.24***			
4. Overlap Set Within-Category RIFO	**-.21***	.08	**.28***		
5. Distinct Set RIFA	-.11	**-.25***	**-.22***	**-.35***	
6. Overlap Set RIFA	.13	**-.33***	**-.32***	**-.27***	**.24***

Table 2. Raw Pearson 2-tailed correlations between RIFO and WMC scores (N = 125).
* Significant value $p < .05$.

4.5 Discussion

We have investigated the relationship between WMC and retrieval-induced effects under conditions of high and low interference. Our design included sets of overlapping and distinct items, directly contrasting the effects of low and high interference resolution demands. Factors that are known to influence RIFO, like output interference and integration, were controlled for by using weak items of low taxonomic frequency. In line with the notion that RIFO is caused by resolving interference during retrieval and the subsequent suppression of features (Anderson & Spellman, 1995), we only found RIFO under conditions of high interference. This is in line with the feature suppression model, which states that an item is less likely to be retrieved when its features are inhibited during retrieval practice.

Our findings also support the notion that WMC differences are reflected in retrieval from long-term memory (Unsworth, Spillers, & Brewer, 2010), by means of controlled search. Low-WMC individuals seemed to enter more irrelevant items into their search set, increasing interference resolution demands, requiring more inhibition, resulting in RIFO within and between overlapping categories. Individuals with high-WMC also exhibited between-category RIFO suggesting the effect of some interference but unlike their low capacity counterparts, high-WMC individuals showed no RIFO for overlapping items within the practiced category. This is consistent with the idea that high-WMC individuals entered fewer irrelevant items into their search set, decreasing interference resolution demands, resulting in no RIFO.

Additionally, in the high interference condition, only high-WMC individuals benefited from retrieval practice, which seems to mirror the RIFO effect. Accessibility of an item is determined by the combined effect of retrieval practice, making certain features more accessible, and inhibition, making features less accessible. While executive control is an important component of WMC differences (Redick et al., 2007) our findings suggest that the ability to delimit the amount of information entered into the search set facilitates retention of practiced information. Only high-WMC individuals were able to effectively retrieve similar items from long-term memory during practice and the final memory test, which was evidenced by the negative correlation of WMC and within-category RIFO when interference was high.

The overall negative correlation between WMC and RIFO on the other hand seems to contradict the recent findings of Aslan and Bäuml (Aslan & Bäuml, 2010) who reported the opposite result, namely more RIFO for individuals with higher WMC. There are two main differences between our experiments that might explain the disparity: First, the recognition test used by Aslan and Bäuml (Aslan & Bäuml, 2010) did not require participants to search their memory but instead to judge familiarity. A recognition test may not require focused search compared to a cued memory test in which retrieving an item based on the correct cue is advantageous. High-WMC individuals would arguably benefit from retrieval cues while a recognition test might have greatly aided low-WMC individuals, affecting the recall rates for both groups. Second, the delay period between retrieval practice and memory test was considerably shorter, 1 minute compared to 25 minutes. Using longer delays (which are more typical of retrieval-induced forgetting tasks (Anderson et al., 1994)), increases the likelihood that individual differences in efficient retrieval from long-term memory can impact RIFO effects. Individual WMC differences have been argued to manifest themselves in short- and long-term memory (Unsworth & Engle, 2007a;

Unsworth et al., 2010) but since consolidation takes time, a short delay between retrieval practice and memory test may leave items more active in short-term memory where executive control may play an important role. Both differences may account for the disparity between our findings and those of Aslan and Bäuml (Aslan & Bäuml, 2010).

The negative correlation between RIFO and RIFA limits the extent to which we can disregard the effects of blocking. When retrieval of a practiced item prevents access to related items, one would expect that people who show RIFA should also show RIFO. Since using weak items has been found to diminish output interference (Bäuml, 1998), it is surprising to find any relationship between RIFA and RIFO for the categories where competition between items was low. However, when the data were split up into extreme groups we observed that under conditions of high interference, low-WMC individuals exhibited strong RIFO but no RIFA and high-WMC individuals showed no RIFO but intact RIFA. No forgetting of competing information and clear benefits of retrieval practice suggests that for high-WMC individuals, the search was limited to more relevant information. To our understanding, the blocking account does not predict this dissociation. Our results therefore fit with earlier studies that found RIFA and RIFO to be largely unrelated (Hanslmayr, Staudigl, Aslan, & Bäuml, 2010; Staudigl, Hanslmayr, & Bauml, 2010): RIFA can occur without RIFO (Anderson et al., 1994; Bauml & Kuhbandner, 2007; Koessler, Engler, Riether, & Kissler, 2009) and RIFO can occur without RIFA (Gómez-Ariza, Lechuga, Pelegrina, & Bajo, 2005; Storm et al., 2006; Veling & Knippenberg, 2004). The dissociation between RIFA and RIFO has also been supported by neuroimaging studies finding different correlates for RIFA and RIFO (Kuhl, Kahn, Dudukovic, & Wagner, 2008; Spitzer & Bäuml, 2009; Wimber et al., 2008). Thus, while we cannot exclude the possibility of output interference playing a role, the overall pattern of results fits well with the notion that inhibitory control was used to resolve competition between information in the search set.

When the inhibitory explanation is considered in conjunction with the focused search hypothesis, one may explain why RIFO is found in populations believed to have low executive control like young children (Ford et al., 2004; Zellner & Bäuml, 2005), people with schizophrenia (Racsmány et al., 2008) or Alzheimer's disease (Moulin et al., 2002). Free recall is often not done in a semantically-clustered fashion for people with schizophrenia (Kareken, Moberg, & Gur, 1996), children (Frankel, Rollins, & others, 1982) and people with Alzheimer's disease (Troyer et al., 1998), which suggests that their search set is not effectively limited by specific retrieval cues. Within such populations, the effect of committing irrelevant items into the search set might amplify the effect of even low executive control, leading to the observed RIFO effects. While it is essential to control for factors such as integration (Goodmon & Anderson, 2011) and output interference (Storm & White, 2010), we stress that it is also important to consider focused search as a prerequisite for any executive control processes to have an effect.

To summarize, our findings lend support to the inhibitory account of RIFO (Anderson et al., 1994, 2000) and the feature suppression model (Anderson & Spellman, 1995). High-WMC individuals seem better able to control interfering information during retrieval from long-term memory which supports the controlled search hypothesis (Unsworth & Engle, 2007a; Unsworth et al., 2010) and adds an important dimension to our understanding of retrieval-induced effects which may explain some disparities in the literature. Knowledge about the contribution of controlled search and executive control in high and low interference contexts could be used to inspire new methods of training, especially for people with low-WMC who, in our experiment, showed the biggest benefit for remembering items with little feature overlap. Likewise, teaching individuals to use appropriate retrieval cues in certain contexts may be explored.

4.6 Appendix

Overlap Set:

SCHERPE, WAPENS	VLIEGENDE, DIEREN
degen	Albatros
floret	Buizerd
glas	flamingo
hakmes	gaai
kris	havik
machete	kip
naald	libel
pen	mees
spies	reiger
vork	specht
werpster	uil
zaag	valk

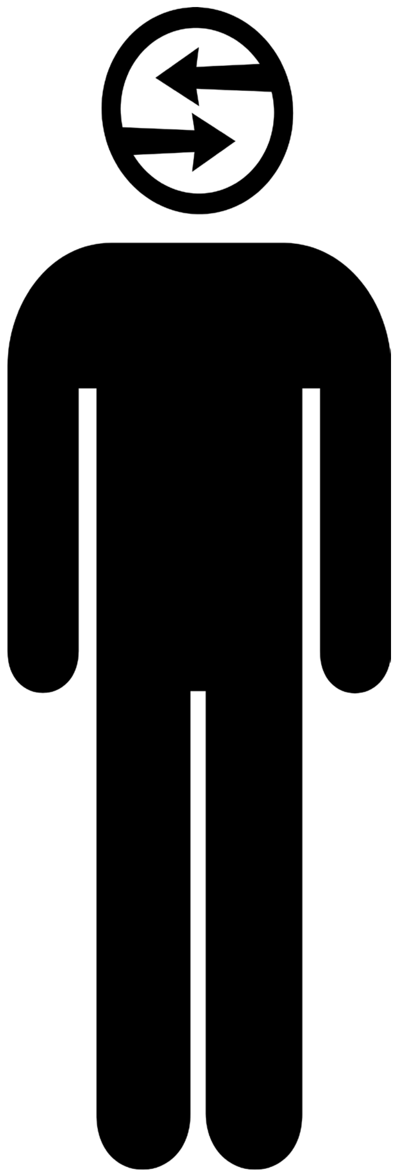
Distinct Set:

HOBBY	ZACHT
toneel	badjas
dans	cavia
gitaar	gras
poolen	poef
rugby	spons
surfen	zeep
KOUD	VOEDSEL
airco	curry
grond	erwt
herfst	honing
iglo	mais
nacht	salade
vorst	vla

Filler:

LUID	ZWEMMEN
applaus	duiker
bus	haring
hoorn	inktvis
kermis	kwal
straat	tonijn
zingen	zalm

Note: OS items were randomly assigned to create categories with six items for each subject.



CHAPTER 5 DISCUSSION

5 DISCUSSION

The individual difference approach for studying the nature of working memory capacity (WMC) has produced much evidence for competing and even contradictory theories. Ultimately, the lack of a unified theory is problematic because it leaves those responsible for the training and application of our mental faculties with conflicting advice regarding the most optimal strategies to do so. What is the most optimal way of giving a lecture and how can individuals with less WMC still perform to the best of their abilities? Fundamentally understanding WMC, the workspace in which we process, retrieve and hold the most relevant information while ignoring distracting stimuli, may aid in accomplishing this worthy goal.

In the current thesis, it is argued that WMC reflects a mainly domain-general resource which represents memory capacity and some attentional control abilities. To support these statements, three empirical chapters are presented. First, simultaneously maintaining stimuli from different domains in working memory provoked substantial interference compared to maintaining stimuli from only a single domain. While spatial memory was uniformly affected by a concurrent verbal load, verbal memory for the last item in the to-be-remembered list, was unaffected by a concurrent spatial load unless a suffix was introduced. Accounting for this asymmetry, working memory may be best understood as a domain-general resource, supplemented by domain-specific sub-systems (Chapter 2). Second, WMC appeared not to index attentional filtering abilities in a visual task. While individuals with low and high-WMC were equally able to attend relevant information, high-WMC individuals seemed to utilize their bigger memory capacity to encode less relevant information when it could benefit performance (Chapter 3). Third, individuals with high-WMC are capable of a more focused memory search. When competition between memory traces during retrieval from long-term memory was strong, low-WMC individuals exhibited retrieval-induced forgetting effects which suggest that they were searching, and hence inhibiting, items in a bigger search set (Chapter 4). Ultimately, in an attempt to synthesize the evidence, a nuanced view of WMC is proposed with an emphasis on storage capacity and task context. The main findings of each chapter are summarized, theoretical considerations discussed and practical implications are presented.

4.7 Chapter 2: Domain Generality

The goal of the study described in Chapter 2 was to evaluate whether memory for serial order was domain-general. Although much research has investigated whether concurrently maintained auditory-verbal and visual-spatial information interferes with each other, results have differed widely. Some found little or no interference (Cocchini, Logie, Sala, MacPherson, & Baddeley, 2002; Logie, Zucco, & Baddeley, 1990) but others have reported strong cross-domain competition for storage resources (Depoorter & Vandierendonck, 2009; Saults & Cowan, 2007; Vergauwe, Barrouillet, & Camos, 2010). To address this question we compared performance between single- and dual-task versions of a serial reconstruction task (Guérard & Tremblay, 2008). The task featured lists of verbal or spatial stimuli (aurally presented nouns and/or random locations on the screen) and the participants' task was to indicate the order in which the stimuli were presented. To measure the interference between two stimulus sets being encoded by different perceptual systems, the task was constructed to make the stimuli as similar as possible in all respects except their sensory domain. Performance was compared between three task variants. The first variant required only a single list to be maintained. The second featured interleaved verbal and spatial stimuli but the participants were cued regarding which domain would be tested. The third variant also featured interleaved verbal and spatial stimuli, but participants were uncued regarding which domain would be tested and therefore attempted to remember both lists. We argued that observing no interference in this variant would be evidence for separate verbal and visual-spatial resources (Shah & Miyake, 1996). Yet, any interference in the uncued dual–task would suggest that domain-general resources were used to maintain or consolidate the incoming stimuli, which was exactly what we found.

The results showed clear dual-task costs when verbal and spatial sequences had to be maintained simultaneously compared to maintaining either sequence alone or when maintaining either sequence while ignoring the other. This cost signifies strong evidence for a domain-general resource underlying serial working memory. However, examining accuracy per serial position, we found an asymmetry for the last serial position. While spatial memory was universally affected by the concurrent verbal load throughout all serial positions, verbal memory was affected for the first and middle serial positions but not for the last.

Two follow-up experiments helped us to better understand this asymmetry. First, we dismissed the contribution of semantic representations of nouns in long-term memory by replicating the dual-task cost pattern using pronounceable non-words as verbal stimuli. Since non-words are very unlikely to have semantic representations, finding the same pattern as in the first experiment suggested that additional activation in long-term memory did not sustain the representation of the last verbal stimulus. Second, we added sensory suffixes after the presentation of the final memoranda which should interfere with information held in a domain-specific short-term store. Consequently, the asymmetry disappeared and we observed dual-task costs throughout all serial positions for both verbal and spatial memory. Thus, we explained the asymmetry for the final verbal item by reliance on a domain-specific resource available to maintain verbal information in a short-term sensory store.

Theoretical implications of these findings are discussed in more detail in section 2.7.2. In the context of this thesis, the evidence presented in chapter 2 provided the practical justification to study WMC as a mainly domain-general resource, likely supplemented by fragile domain-specific sub-systems. Based on this conclusion, it was evident that a useful operationalization of WMC should limit the contribution of domain-specific sub-systems. Therefore, a decision was made to combine two complex span tasks, one using spatial and the other using verbal memoranda to reflect an individual's WMC. The composite WMC score, which is used in the following studies, thereby reflects an individual's general ability to maintain information under concurrent processing demands.

4.8 Chapter 3: Attentional Control

As a general resource, WMC is strongly related to cognitive tasks that have low memory demands but require executive abilities (Hutchison, 2007; Jarrold & Towse, 2006; Unsworth, Schrock, & Engle, 2004). Whereas some have interpreted such findings to mean that WMC is determined by the ability to control attention (Engle, Kane, & Tuholski, 1999; Kane et al., 2004; Kane, Conway, Hambrick, & Engle, 2007), others have emphasized the role of storage capacity (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008).

In this chapter, we examined whether WMC can predict effective attentional control. Evidence regarding the relationship between WMC and selective attention in various contexts was discussed, revealing major differences in the formulation of boundary conditions. While WMC predicted auditory selective attention only when the distraction was irregular or semantically related to the relevant information (Beaman, 2004; Hughes, Hurlstone, Marsh, Vachon, & Jones, 2012; Sörqvist, Marsh, & Nöstl, 2013; Sörqvist, 2010), in visual selective attention, WMC is often described as directly related to the ability to ignore any irrelevant information(Awh & Vogel, 2008; Vogel, McCollough, & Machizawa, 2005).

To reconcile these diverging interpretations, a visual change detection task was administered with different degrees of attentional filtering and allocation requirements. The task featured an always equal number of two different shapes, colored circles and triangles. After a brief presentation of the shapes, participants had to maintain the location of the colors for several seconds before being presented with the probe screen where the outline of all studied shapes appeared and one shape was coloured and the participant had to indicate whether its color had changed. The relevance of each shape was manipulated in several blocks by being tested with varying frequency. If WMC was directly related to selective attention, individuals with high-WMC were expected to ignore less relevant information, while low-WMC individuals should be unable to filter efficiently and would inadvertently look at (and perhaps encode) the less relevant information.

Counter to the notion that WMC indexes attentional control abilities, eye-tracking data revealed that individuals with high-WMC actually focused significantly more on less relevant stimuli than people with low-WMC. Since high-WMC individuals are generally quite able to focus (Conway, Cowan, & Bunting, 2001) or efficiently divide their attention (Colflesh & Conway, 2007), it appeared that high-WMC individuals were utilizing their superior storage capacity to encode as much information as possible to improve overall performance.

Further support for the notion that high-capacity individuals tried to maximize performance using their superior storage capacity was found in the second experiment when a strong incentive for selective attention was introduced. Giving participants more points for a particular shape, which translated into a reduction of total experiment time, removed the relationship between WMC and looking at less relevant information. Since participants across the spectrum of WMC scores responded similarly to the incentive, Bayes factor analyses produced strong evidence for the null hypothesis that individuals across the spectrum behaved similarly. Thus, when the task featured a strong incentive to use attentional control and not use excess storage capacity to maximize performance, low and high-WMC individuals controlled their attention equally well.

Another possibility was that constantly presenting distractors may have acted as a reminder for the task goal, eliminating the effect of variation in the propensity to maintain the task goal (Hutchison, 2011; Morey et al., 2012). Although it is unclear whether goal maintenance differences are caused by attentional control or storage capacity, it seems plausible that high-WMC individuals could use their extra capacity to proactively maintain the task goal (Braver, 2012).

In conclusion, the findings challenge the generalized claim that low-capacity individuals cannot efficiently control attention (McNab & Klingberg, 2008; Vogel et al., 2005) and suggest that under the right circumstances, low-capacity individuals strategically preserve their limited storage capacity for relevant information. Individual differences in WMC may therefore not be directly determined by attentional control abilities. Instead, storage capacity seems to shape the advantages that people with high-WMC exhibit. Whereas chapter 3 has discussed how WMC and retrieval from short term memory interact, chapter 4 discusses the relationship between WMC and long-term memory.

4.9 Chapter 4: Focused Search

In the previous chapter it was argued that much of the evidence brought forward in support of the notion that WMC and attentional control are directly related (e.g. Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003) could also be explained in terms of storage capacity and goal maintenance differences. Whereas chapter 3 discussed additional evidence from visual short-term memory, executive control processes are also believed to influence retrieval from long-term memory when task irrelevant information needs to be inhibited (Redick, Heitz, & Engle, 2007). One paradigm that indexes inhibition of task irrelevant information is the retrieval practice paradigm.

In the retrieval practice paradigm, participants first study a number of word pairs (e.g. hobby – rugby) from different categories, then they engage in retrieval practice in which half the words from some categories have to be retrieved (e.g. hobby – r___), and finally, memory is tested for all associations. The retrieval-induced forgetting (RIFO) effect is the difference in performance between the items that were never tested during the practice phase and those that were related to the tested items. The RIFO effect is believed to be due to inhibitory executive-control processes that occur during the retrieval practice phase (Anderson, 2003), when resolving interference of competing memory representations is necessary to retrieve the correct item.

With regards to executive control abilities and RIFO effects, earlier findings have been mixed. Aslan and Bäuml, (2010) reported a positive correlation between RIFO and WMC, which they argue was due to stronger inhibitory executive control in high-capacity individuals. Groome, Thorne, Grant and Pipilis, (2008) on the other hand found no relationship between the capability to inhibit intrusive thoughts and RIFO. A possible explanation for such discrepancies might be found when considering that inhibition comprises different sub-processes (Friedman & Miyake, 2004) and it is controlled search, as related to resistance to proactive interference that may diminish the need for inhibition. To illustrate, in cued recall, low-WMC individuals recall fewer items, make more errors, and have longer recall latencies than high-WMC individuals (Unsworth & Spillers, 2010; Unsworth, 2009). Thus, high-capacity individuals seem to successfully delimit their search set, possibly by using more specific retrieval cues (Unsworth & Engle, 2007b), which makes it less necessary to use inhibition for retrieval in settings where specific retrieval cues are beneficial.

The executive control and focused memory search hypotheses make contrasting predictions regarding RIFO effects and WMC, as the use of specific retrieval cues would diminish the need for inhibition. We furthermore argued that integration and output interference are possible sources of individual differences which, among other methodological considerations, may explain the positive relationship between WMC and RIFO previously described (Aslan & Bäuml, 2010). Our study aimed to answer these questions by using the retrieval-induced forgetting paradigm and controlling for additional sources of variance. To manipulate the amount of competition between the to-be-retrieved items, we created distinct and overlapping categories and we used weak exemplars to ensure negligible effects of output interference and integration.

The results showed that contrary to Aslan and Bäuml's (2010) findings, under conditions of high interference (i.e. recalling items from overlapping categories), high-WMC individuals showed no RIFO and low-WMC individuals exhibited strong RIFO. The focused search hypothesis fits with the finding of within-category RIFO for only low-capacity individual while global RIFO between categories indicates that that inhibitory control was used by all participants to resolve competition between information in the search set. Since the low capacity group appeared unable to delimit the search set, the need to suppress a greater number of memory traces was illustrated by the cumulative effect of inhibition during retrieval, resulting in RIFO. High-WMC individuals on the other hand limited their search set and did not need to exert as much executive control when competition was high. Interestingly, the benefit of delimiting the search set seemed to expand to the positive effects of retrieval practice. Under conditions of high interference, high-capacity individuals performed better on practiced items while low-capacity individuals only benefitted from practice when interference was low. This asymmetry again illustrated that for high-WMC individuals, the search was limited to more relevant information whereas low-WMC appeared to consider irrelevant information also.

As in chapter 3, we found that certain aspects of executive control were not indexed by WMC. High-capacity individuals appeared to focus their memory search (Unsworth & Engle, 2007a; Unsworth, 2007) while inhibition of irrelevant representations was found across the spectrum of WMC. The reason why high-capacity individuals may be able to use more appropriate retrieval cues can again be explained by storage capacity differences. First, larger capacity may increase the number of associations with to-be-remembered items (e.g. context cues), thereby increasing the chance to encode the cues which are most helpful during retrieval. Second, during encoding and retrieval practice, being able to consider a greater number of representations could help to integrate groups of items. In this way, storage capacity may enable strategic encoding (Bailey, Dunlosky, & Kane, 2008). Evidence for the first possibility was reported by Unsworth, Brewer and Spillers, (2011) who used a paired associates cued recall task with either a rhyme or semantic cue presented during encoding. When cues at encoding and retrieval matched, high-WMC individuals were much better than low-WMC individuals but a cue mismatch led to equivalent performance (see also Delaney & Sahakyan, 2007). The second possibility, regarding integration, could explain why in our study, practice under conditions of strong interference only benefitted high-WMC individuals as, through integration, they may have used practiced items as the retrieval cues for other items. Since high-WMC individuals report using a number of different strategies (rehearsal, imagery, grouping, etc.) when encountering lists of words (Bailey et al., 2008) both contextual-retrieval abilities (Unsworth & Engle, 2007b) and strategic encoding may contribute to their performance advantage. In summary, the ability to delimit the search set is related to WMC and can be explained by high-WMC individuals utilizing their superior storage capacity.

4.10 General Discussion

The findings presented in chapters 2-4 and discussed above led to the conclusion that WMC is best defined as a domain-general resource with some reliance on domain-specific sub-systems. As such, our findings emphasize the importance of storage capacity and focused search in WMC differences. In the context of individual differences in WMC it appears that attentional control abilities can also be explained by evoking storage capacity differences which affect performance in two ways. First, more storage capacity can enable individuals to maintain appropriate goal states and stimulus response mappings. Second, storage capacity can aid the retrieval process by allowing for the creation of context cues and advanced encoding strategies. Both aspects are important in performing complex operations, which is reflected in the strong relationship between WMC and higher order cognitive skills (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Daneman & Carpenter, 1980; Jarrold & Towse, 2006).

Embedded models of memory and attention (Cowan, 1995, 2005; Oberauer, 2002, 2006) can partly explain such findings. These models posit that WMC is a subset of long-term memory, characterized by strong activation that aids more rapid retrieval. Memory objects or task goals could be represented by this activation. Thus, individual differences in WMC may index the number of chunked objects that can be held in the focus of attention or their activation longevity (Cowan, 2005). Alternatively, the domain-general episodic buffer, which is the most recent addition to Baddeley's working memory model, might serve the same purpose (Baddeley, 2000, 2001). The critical difference between the embedded processes and multicomponentconception of WMC and the attentional control hypothesis (Engle et al., 1999) is their emphasis on the underlying reason for capacity limits. Whereas the strong interpretation of the attentional control hypothesis suggests that low-WMC individuals haphazardly encode irrelevant information (Awh & Vogel, 2008), leading to a measurement of smaller capacity for relevant information, we found in chapter 3 that the ability to ignore irrelevant information was present irrespective of WMC. Such "good news" for low-WMC individuals may nevertheless be contingent on specific task contexts which should not overload their capacity to maintain the task goal (Hutchison, 2011; Kane & Engle, 2003; Morey et al., 2012). As of yet, the asymmetry in short-term serial recall, discussed in chapter 2 and the boundary conditions for visual selective attention outlined in chapter 3 have yet to be incorporated in working memory models (see the discussions of chapter 2 and 3 for details).

Future studies should address these issues. For example, by testing whether the asymmetry in serial recall, discussed in chapter 2, may stem from a life-long practice of rehearsing verbal information (Logie, Cocchini, Delia Sala, & Baddeley, 2004). This could be accomplished by administering versions of our dual-tasks to a deaf or very young population. Whether such avenues will lead to a more parsimonious conception of memory, for example within a perceptual-gestural framework (Hughes, Marsh, & Jones, 2009) is unknown. In light of our findings however, a compromise between models focusing on domain-specificity or domain-generality seems inevitable. Likewise, more research is needed to formulate clear boundary conditions for visual selective attention as discussed in chapter 3. Even though it was discussed that distraction appears to only affect low-WMC individuals when it is salient and unexpected (Fukuda & Vogel, 2009; Sörqvist, 2010), distraction can also act as a reminder of the task goal which especially aids low-WMC individuals. Furthermore, it appears possible that distractors are always encoded when perceptual load is low or WMC is high (Forster & Lavie, 2011; Lavie, Hirst, de Fockert, & Viding, 2004). Accounting for these factors and disentangling their respective influence in future studies is imperative. Lastly, a better understanding of the relationship between WMC and retrieval specificity may have direct practical implications. Since focused search through the creation of specific retrieval cues appeared to benefit both resilience to high interference and the effect of practice, the next step ought to be the replication of these findings in a teaching environment. For example, teachers may want to ensure minimal exposure to unrelated facts during teaching. Future research may therefore compare various approaches to blocked learning and try to teach strategies that increase the use of contextual cues. The insights obtained by such approaches will hopefully lead to better learning environments for people across the spectrum of WMC.

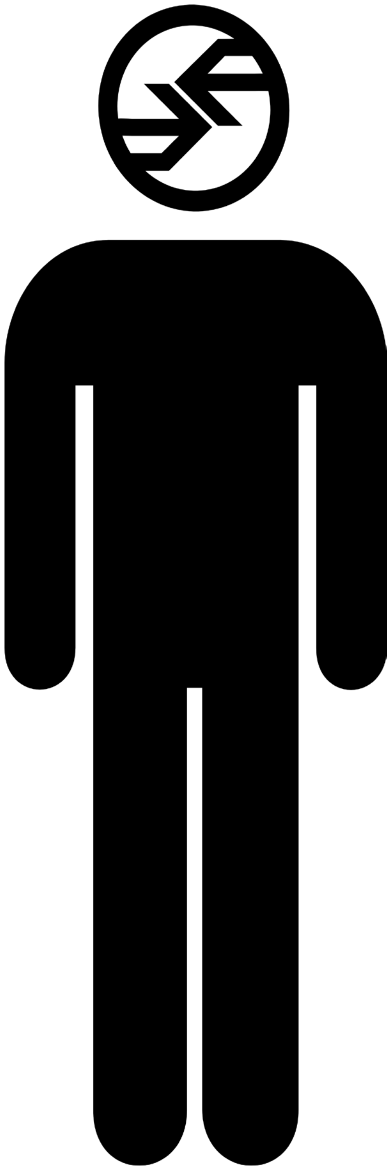
The practical lessons from our findings are numerous. It appears that WMC does not need to be a limiting factor for learning, as under the right conditions, people with low and high-capacity can perform remarkably similarly. Nevertheless, low capacity individuals in particular may benefit from environments without unexpected distraction. Thus, leaving the TV on during study periods, will likely pose an unnecessarily strong distraction. Likewise, as illustrated by irrelevant sound effects (Beaman, 2004), low-WMC individuals may be advised not to listen to music that contains irregularly occurring vocals (e.g. rap music) since it is more likely to capture their attention, potentially leading to the temporary loss of the current task goal. While high-WMC individuals appear to be more resilient to distractors, they do not appear immune, especially if distraction is created internally, e.g. worrying about the outcome of a test (Beilock & Carr, 2005). Therefore, ensuring limited external and internal distraction is likely to benefit both low and high-WMC individuals. Such practical suggestions are also supported by cognitive load theory, which states that factors leading to WM overload strongly interfere with effective learning (Paas, van Gog & Sweller, 2010)

Additionally, a conflict rich environment was shown to aid the maintenance of the task goal (Hutchison, 2011; Morey et al., 2012). Translated to a real life situation, e.g. commuting on the road, using numerous salient speed limit signs seems like a good idea. However, since maintaining the speed limit might occupy storage, this manipulation might be contingent on a statistically beneficial trade of between remembering the speed limit and noticing an unexpected object on the road.

It remains an interesting question whether one can reap the benefits of having high-WMC by getting better at performing WMC tasks. Although early reports were encouraging, finding a modest increase in a measure of intelligence after a week of working memory training (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). However, since the task used to measure intelligence was in some respects quite similar to the WMC task, it remains unclear whether the improvement on the fluid intelligence test represented an increase of intelligence or merely an increase in test-taking skills (Moody, 2009). At this point, teaching pupils effective encoding and learning strategies seems more effective than administering WMC training.

Lastly, it should be noted that people might be quite aware that their WMC resources are limited, leading them to compensate strategically. As discussed in chapter 3, low-WMC individuals seemed to preserve their capacity for the most relevant information. It is possible therefore that high-WMC individuals may excel at difficult tasks because they utilize extra capacity to proactively keep task goals activated (e.g. Braver, 2012). However, low-WMC individuals can be instructed to adopt beneficial encoding strategies. When asked to remember a list of words which at test were cued by some of the learned words, low-WMC individuals performed on the same level as high-WMC individuals when they were told to encode the words using a story to connect them (Cokely, Kelley, & Gilchrist, 2006). In the summary of chapter 4, we discussed how strategic encoding benefits high-WMC individuals (Bailey et al., 2008). Since strategic encoding may also increase an individual's complex span performance, by combining letters into a word or creating a meaningful shape out of spatial locations, it remains to be seen how much the tendency to employ advanced encoding strategies influences the relationship between WMC and other cognitive abilities.

In conclusion, the studies presented in this thesis add to our understanding of the structure and variability of WMC. Theoretical models may require reorganization and new boundary conditions for the interaction between WMC and selective attention need to be integrated. Some of the findings may inspire the creation of learning and work environments that cater to the needs and abilities of people across the spectrum of WMC. Ultimately, when applying the right strategy, people with different abilities can perform remarkably similarly.



CHAPTER 6 DUTCH SUMMARY / NEDERLANDSE SAMENVATTING

5 NEDERLANDSE SAMENVATTING

De individuele verschil benadering van het werkgeheugen (WG) heeft ondersteuning voor concurrerende en zelfs tegenstrijdige theorieën opgeleverd. Uiteindelijk is het gebrek van een omvattende theorie problematisch, omdat het degenen die verantwoordelijk zijn voor opleiding en training van onze mentale vermogens met tegenstrijdige adviezen opgezadeld worden. Wat is de optimale manier om een lezing te geven en hoe kunnen mensen met minder WG toch het beste uit hun vaardigheden halen. Een beter begrip van WG, de vaardigheid om relevante informatie bij te houden terwijl afleidende stimuli genegeerd moeten worden, zal helpen om dit hoge doel te bereiken.

In dit proefschrift wordt betoogd dat WG het beste kan worden begrepen als een domein-algemene resource die de geheugencapaciteit en aandachtscontrole weerspiegeld. Om deze veronderstelling te steunen, worden drie empirische hoofdstukken gepresenteerd. Ten eerste, het tegelijkertijd bijhouden van informatie uit verschillende domeinen veroorzaakt aanzienlijke interferentie in het werkgeheugen vergeleken met het bijhouden van informatie uit slechts één domein. Terwijl geheugen voor ruimtelijke informatie gelijkmatig werd aangetast door gelijktijdig gepresenteerde verbale informatie, was het verbale geheugen voor het laatste item niet beïnvloed door gelijktijdige ruimtelijke informatie, tenzij een suffix werd toegevoegd. Deze asymmetrie in het werkgeheugen kan het beste worden begrepen door te veronderstellen dat WG domein-algemeen is, ondersteund door domeinspecifieke subsystemen (hoofdstuk 2). Ten tweede, WG bleek geen aandachtscontrole in een visuele taak te indexeren. Terwijl mensen met zowel een laag als hoog WG even in staat waren om relevante informatie bij te houden, leken hoog WG individuen hun grotere geheugencapaciteit te gebruiken om ook minder relevante informatie op te slaan wanneer de algemene prestatie ervan zou profiteren (hoofdstuk 3). Ten derde, mensen met een hoog WG zijn in staat om meer gericht in hun geheugen te zoeken. Wanneer tijdens het ophalen van item uit het lange termijn geheugen de competitie tussen items hoog was, bleken de laag WG individuen ophaal-geïntoduceerde effecten te vertonen die suggereren dat ze door een groter aantal items moesten zoeken, waardoor de activiteit van deze extra items moest inhiberen (hoofdstuk 4). In drie empirische hoofdstukken worden factoren onderzocht die ten grondslag aan WG liggen. Verder wordt de relatie tussen hogere cognitieve vaardigheden en WG onderzocht. Uiteindelijk wordt een poging ondernomen om de resultaten samen te brengen naar een genuanceerd beeld van WG dat nadruk legt op opslagcapaciteit en taak context. De belangrijkste bevindingen van elk hoofdstuk worden nu samengevat, theoretische overwegingen worden besproken en praktische implicaties worden gepresenteerd.

5.1 Hoofdstuk 2 Domein Generaliteit

Het doel van hoofdstuk 2 was om te evalueren of het geheugen voor seriële orde domeingeneraal was. Hoewel in veel studies werd onderzocht of het gelijktijdig onthouden van auditief-verbale en visueel-ruimtelijke informatie met elkaar interfereert, bleken de resultaten nogal verschillend. Sommigen vonden weinig of geen interferentie (Cocchini, Logie, Sala, MacPherson, & Baddeley, 2002; Logie, Zucco, & Baddeley, 1990), terwijl andere sterke interferentie tussen domeinen hebben aangetoond (Depoorter & Vandierendonck, 2009 hebben gemeld; Saults & Cowan, 2007; Vergauwe, Barrouillet, en Camos, 2010). Om deze vraag te beantwoorden vergeleken we de prestaties tussen enkel- en duaal-taak versies van een taak waarin de seriële wederopbouw getest werd (Guerard & Tremblay, 2008). In de taak werden lijsten gebruikt van verbale of ruimtelijke stimuli (auditief gepresenteerd zelfstandige naamwoorden en / of willekeurige locaties op het scherm), terwijl deelnemers de volgorde van de stimuli moesten onthouden. Om de interferentie tussen de stimuli te meten die door verschillende perceptuele systemen werden geëncodeerd, werd de taak zodanig geconstrueerd dat de stimuli zo nauw mogelijk gelijk waren behalve in hun zintuiglijke domein. Prestaties werden vergeleken tussen drie varianten van de taak. De eerste variant vereiste slechts dat een enkele lijst werd onthouden. De tweede variant had verbale en ruimtelijke stimuli die samen werden gepresenteerd, terwijl de deelnemers dankzij een cue van tevoren wisten welk domein zou worden getest. De derde variant was ook gekenmerkt door gelijktijdige verbale en ruimtelijke prikkels, maar de deelnemers waren niet ge-cued welk domein zou worden getest en moesten daarom proberen om beide lijsten te onthouden. Onze verwachting was dat als er in de laatste variant geen daling in prestatie was, er aparte verbale en visueel-ruimtelijke middelen waren om de informatie te onthouden (Shah & Miyake, 1996). Als er enkel daling in prestatie zou zijn in de variant waarin niet gecued werd, zou het suggereren dat domein-algemene middelen werden gebruikt om de binnenkomende informatie te onthouden of te consolideren. Dit is precies wat we hebben gevonden.

De resultaten toonden aan dat er duidelijke dual-taak meer kosten waren als verbale en ruimtelijke stimuli tegelijkertijd moesten worden onthouden, dan met het onthouden van maar een van de sequenties, terwijl de andere genegeerd moest worden. Deze kosten zijn een sterke aanwijzing voor een domein-algemene basis van het seriële werkgeheugen. Echter, toen wij naar de prestatie per seriële positie keken, vonden we een asymmetrie voor de laatste seriële positie. Terwijl het ruimtelijke geheugen over alle seriële posities door de gelijktijdige verbale belasting werd beïnvloed, werd het verbale geheugen wel op de eerste en middelste seriële posities aangetast, maar niet op de laatste positie.

Twee vervolg experimenten hebben ons geholpen om deze asymmetrie beter te begrijpen. Ten eerste konden wij uitsluiten dat er een bijdrage was van semantische representaties van de zelfstandige naamwoorden in het lange termijn geheugen door het patroon van dual-taak kosten te repliceren met behulp van uitspreekbare non-woorden als verbale stimuli. Aangezien non-woorden geen semantische vertegenwoordiging hebben, en wij toch hetzelfde patroon als in het eerste experiment konden vinden, lijkt activatie in het langetermijngeheugen de vertegenwoordiging van de laatste verbale stimulus niet te ondersteunen. Ten tweede hebben we na de presentatie van de laatste item een zintuiglijke achtervoegsels (suffix) toegevoegd waarmee de representatie in een domein-specifiek geheugen verstoord zou moeten worden. Deze manipulatie liet de asymmetrie verdwijnen. Hiermee hebben wij de asymmetrie verklaard door te stellen dat voor verbale informatie een domein-specifiek zintuiglijke geheugen systeem aanwezig is.

Theoretische implicaties van deze resultaten worden nader in paragraaf 2.8 besproken. In het kader van dit proefschrift, kan hoofdstuk 2 worden begrepen als de theoretische rechtvaardiging om WG als een hoofdzakelijk domein-algemene resource te bestuderen, die waarschijnlijk aangevuld wordt met fragiele domeinspecifieke subsystemen. Op basis van deze conclusie, was het duidelijk dat een bruikbare operationalisering van WG de bijdrage van domein-specifieke sub-systemen moeten beperken. Daarom werd besloten om twee complexe geheugen taken te combineren, de ene gebaseerd op ruimtelijke en de andere gebaseerd op verbale memoranda, om het WG van een individu te weerspiegelen. De samengestelde WG score, wordt in de volgende studies gebruikt en weerspiegelt het vermogen van een individu om informatie onder gelijktijdige verwerkingseisen bij te houden.

5.2 Hoofdstuk 3 Aandachtscontrole

Als algemene resource, blijkt WG sterk geassocieerd met cognitieve taken die weinig geheugen maar wel executieve functies vereisen (Hutchison, 2007; Jarrold & Towse, 2006; Unsworth, Schrock, & Engle, 2004). Sommige hebben dergelijke resultaten als bewijs gebruikt om te bewijzen dat het WG vooral wordt bepaald door het vermogen om aandacht te controleren (Engle, Kane, en Tuholski, 1999; Kane et al., 2004. Kane, Conway, Hambrick, en Engle, 2007), anderen hebben echter benadrukt dat opslagcapaciteit een belangrijke rol speeld (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008).

In dit hoofdstuk, hebben mijn collega's en ik onderzocht of WG effectieve aandachtscontrole kan voorspellen. Resultaten met betrekking op de relatie tussen WG en selectieve aandacht werden besproken, waaruit duidelijk werd dat er grote verschillen zijn in de formulering van randvoorwaarden. Terwijl WG auditieve selectieve aandacht alleen kan voorspellen wanneer de afleiding onregelmatig gepresenteerd of semantisch gerelateerd aan de relevante informatie was (Beaman, 2004; Hughes, Hurlstone, Marsh, Vachon, & Jones, 2012; Sörqvist, Marsh, & Nöstl, 2013; Sörqvist, 2010) , wordt door anderen beweerd dat WG en visuele selectieve aandacht zonder beperkingen gerelateerd zijn (Awh & Vogel, 2008; Vogel, McCollough, & Machizawa, 2005).

Om deze uiteenlopende interpretaties met elkaar te verzoenen, hebben wij een visuele verandering detectie taak toegevoegd waarin verschillende gradaties van aandachtscontrole vereist werden. De taak had een altijd gelijk aantal van twee verschillende vormen; gekleurde cirkels en driehoeken. Na een korte presentatie van de vormen moesten proefpersonen de locatie van de kleuren enkele seconden onthouden voordat de omtrek van alle vormen weer gepresenteerd werd. Een van de vormen was gekleurd en de deelnemer moest aangeven of de kleur was gewijzigd ten opzichte van de eerdere presentatie. De relevantie van elke vorm werd gemanipuleerd door de vormen in verschillende blokken met wisselende frequentie te testen. Dus, als WG direct gerelateerd is met selectieve aandacht, zouden individuen met hoge WG minder relevante informatie kunnen negeren, terwijl individuen met laag WG naar minder relevante informatie zullen kijken (en misschien coderen).

In tegenstelling tot het idee dat WG en aandachtscontrole hetzelfde zijn, toonden de gegevens van de eye-tracker aan dat personen met een hoog WG vaker naar minder relevante vormen keken dan mensen met een laag WG. Aangezien individuen met een hoog WG over het algemeen goed in staat zijn om niet relevante informatie te negeren (Conway, Cowan, & Bunting, 2001) of hun aandacht efficiënt te verdelen (Colflesh & Conway, 2007), concludeerden wij dat personen met een hoog WG hun superieure opslagcapaciteit gebruikten om zoveel mogelijk informatie te coderen die hun prestaties kon verbeteren.

Het idee dat individuen met een hoge capaciteit probeerden hun prestatie te maximaliseren werd door de resultaten uit het tweede experiment ondersteund. Door deelnemers meer punten voor een bepaalde vorm te geven, wat zich vertaalde in een vermindering van de totale experimentele tijd, verdween de relatie tussen WG en het kijken naar minder relevante informatie. Aangezien alle deelnemers nu even veel naar de verschillende vormen keken, steunden Bayes factor analyses de nulhypothese, dat individuen over het hele spectrum van WG scores van vergelijkbare waardes vertoonden. Dus, als de taak werd gekenmerkt door een sterke prikkel om aandachtscontrole te gebruiken, en niet om opslagcapaciteit te gebruiken om de prestatie te maximaliseren, beheersten individuen met een laag en hoog WG hun aandacht even goed.

Bovendien was het mogelijk dat de voortdurend gepresenteerde afleiders een herinnering voor het doel van de taak hebben voorgesteld, wat de variatie in de neiging om taak doelen te kunnen handhaven zou laten verdwijnen (Hutchison, 2011.; Morey et al., 2012). Hoewel het onduidelijk is of de vaardigheid om taak doelen bij te houden veroorzaakt word door aandachtscontrole of opslagcapaciteit, lijkt het aannemelijk dat individuen met een hoog WG hun extra capaciteit zouden kunnen gebruiken om pro-actief het taak doel bij te houden (Braver, 2012).

Kortom, de bevindingen staan, in tegenstelling tot de bewering dat individuen met een laag WG capaciteit hun aandacht niet efficiënt kunnen controleren (McNab & Klingberg, 2008; Vogel et al., 2005). Echter, onder de juiste omstandigheden kunnen individuen met een lage capaciteit hun beperkte opslagcapaciteit strategisch inzetten om alleen maar relevante informatie bij te houden. Individuele verschillen in WG worden dus niet direct bepaald door de vaardigheid om aandachtscontrole uit te oefenen. In plaats daarvan lijkt de grote van opslagcapaciteit dezelfde voordelen laten zien die mensen met een hoog WG vertonen. Terwijl in hoofdstuk 3 werd besproken hoe WG en het ophalen van korte termijn informatie in verband staan, zal in hoofdstuk 4 worden ingegaan op de relatie tussen WG en het lange-termijn geheugen.

5.3 Hoofdstuk 4 Gefocused zoeken

In het vorige hoofdstuk is betoogd dat een groot deel van de bevindingen het idee ondersteunden dat WG en aandachtscontrole rechtstreeks samen hangen (bv. Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003), ook in termen van opslagcapaciteit en doel onderhoud kan dit worden verklaard. Terwijl hoofdstuk 3 aanvullende bevindingen van visuele korte-termijn geheugen heeft gepresenteerd, werd ook verondersteld dat executieve processen een rol spelen in het oproepen van herinneringen uit het lange-termijn geheugen, vooral als taak irrelevante informatie moet worden geinhibeerd (Redick, Heitz, & Engle, 2007). Een paradigma dat het onderdrukken van irrelevante herinneringen meet is het "retrieval induced forgetting" paradigma, of naar het Nederlands vertaald: vergeten door herinneren.

Het vergeten door herinneren paradigma heeft verschillende fasen. In de leerfase oefenen de deelnemers een aantal woordparen (bv. hobby - rugby) uit verschillende categorieën. Vervolgens is er een oefenfase waarin de helft van de woorden uit sommige categorieën geoefend worden (bijv. hobby - r___). Tenslotte is er een testfase waarin alle woorden die in de leerfase aan bod kwamen gerapporteerd moesten worden. Het zogenoemde retrieval induced forgetting effect (RIFO) is het verschil in prestaties tussen de woorden uit de categorieën die niet in de oefenfase gepresenteerd werden en de woorden die gerelateerd zijn aan de woorden die wel werden geoefend. Het Rifo effect is volgens de inhibitietheorie (Anderson, 2003) te wijten aan onderdrukkingsprocessen die tijdens de oefenfase optreden als de interferentie tussen concurrerende herinneringen moet worden opgelost door de opgeroepen woorden die niet bij de actuele cue (in dit geval het sleutelwoord) passen te onderdrukken.

Met betrekking tot executieve vaardigheden en Rifo effecten, blijken de bevindingen te variëren. Aslan en Bäuml, (2010) rapporteerde een positieve correlatie tussen Rifo en WG, wat zij wijten aan de vaardigheid van individuen met een hoog WG om meer executieve controle uit te kunnen oefenen door niet relevante herinneringen sterker te onderdrukken. Groome, Thorne, Grant en Pipilis, (2008), anderzijds, konden geen relatie vinden tussen de vaardigheid om ongewenste gedachten te onderdrukken en Rifo. Een mogelijke verklaring voor deze verschillen kan worden gevonden als men veronderstelt dat executieve processen uit verschillende deelprocessen bestaan en bijvoorbeeld weerstand tegen pro-actiefe interferentie gekoppeld is met de vaardigheid om meer gefocust in herinneringen te zoeken (Friedman en Miyake, 2004). Dat zou betekenen dat gefocust in herinneringen zoeken de noodzaak verlaagd om ongewenste herinneringen te onderdrukken. Een goede illustratie van dit idee is dat, in het oproepen van informatie die met cues geleerd werden, individuen met een laag WG minder herinneren, meer fouten maken en tragere reacties vertonen dan individuen met een hoog WG (Unsworth & Spillers, 2010; Unsworth, 2009). Dus, individuen met een hoog WG lijken een minder grote hoeveelheid van items te doorzoeken, waarschijnlijk dankzij het gebruik van specifieke oproep cues (Unsworth & Engle, 2007b), waardoor het minder noodzakelijk is om niet relevante items te onderdrukken.

De executieve controle en gefocusseerd zoeken hypothese maken contrasterende voorspellingen over Rifo effecten en WG, omdat het gebruik van specifieke oproep cues de behoefte om niet relevante informatie te onderdrukken zou verlagen. Verder is het waarschijnlijk dat andere bronnen van individuele verschillen, zoals integratie en output interferentie, zouden kunnen verklaren waarom eerder onderzoek een positieve relatie tussen WG en Rifo heeft gevonden (Aslan & Bäuml, 2010). Onze studie had als doel om de samenhang van WG en Rifo te onderzoeken met behulp van het “retrieval induced forgetting” paradigma terwijl de voor de invloed van extra bronnen van variantie gecontroleerd werd. Om de mate van competitie tussen bepaalde woord categorieën te manipuleren hebben wij én voor verschillende (bijv. hobby & koud) én voor overlappende categorieën gekozen (bijv. scherp & wapen) terwijl het gebruik van zwakke exemplaren de output interferentie en bovendien de integratie van woorden heeft vermindert.

In tegenstelling tot Aslan en Bäuml's (2010) bevindingen toonden onze resultaten aan dat wanneer sterke interferentie aanwezig was (d.w.z. Dat items uit overlappende categorieën werden opgeroepen) individuen met een hoog WG geen Rifo vertonden en individuen met laag WG een sterk Rifo effect vertoonden. De gefocusseerd zoeken hypothese past goed bij binnen-categorie Rifo voor alleen de individuen met een laag WG, terwijl een even groot tussen categorie een Rifo effect aangeeft dat beide groepen woorden hebben onderdrukt om competitie op te lossen. De groep met een lage capaciteit bleek dus niet in staat om de hoeveelheid van items die doorzocht werden te verkleinen. De noodzaak om een groter aantal geheugensporen te onderdrukken werd geïllustreerd door het cumulatieve effect van onderdrukken tijdens het oproepen, wat resulteerde in Rifo. Individuen met een hoog WG beperkten het aantal aantal geheugensporen en hoefden minder executieve controle uit te oefenen toen de competitie tussen woorden hoog was. Interessant was dat degene die blijkbaar minder geheugensporen moesten doorzoeken positieve effecten van de oefenfase vertoonden. Wanneer de competitie hoog was bleken de individuen met hoge capaciteiten beter te presteren op items die geoefend waren terwijl de individuen met een lage capaciteit alleen profiteerden als de competitie laag was. Deze asymmetrie illustreerde nogmaals dat voor individuen met een hoog WG de zoektocht beperkt was tot relevante informatie terwijl individuen met een laag WG ook irrelevante informatie gingen doorzoeken.

In hoofdstuk 3 hebben we vastgesteld dat bepaalde aspecten van executieve controle niet direct in verband staan met het WG. Hoge-capaciteit individuen bleken hun geheugen gefocust te kunnen doorzoeken (Unsworth & Engle, 2007a; Unsworth, 2007), terwijl het onderdrukken van irrelevante informatie door beide groepen werd gedaan. De reden waarom individuen met een hoog WG beter in staat zijn om alleen de relevante informatie op te roepen kan weer worden verklaard door verschillen in hun opslagcapaciteit. Ten eerste kan een grotere capaciteit het aantal associaties verhogen die met de woorden die herinnerd moeten worden in verband staan (bv. contextcues), waardoor de kans verhoogd word om de cues te coderen die tijdens het oproepen van belang zijn. Ten tweede stelt een grotere capaciteit een individu in staat om tijdens de oefenfase een groter aantal gepresenteerde items tegelijkertijd te onthouden waardoor ze gemakkelijker in groepen geïntegreerd kunnen worden. Op deze wijze kan opslagcapaciteit helpen om strategisch te encoderen (Bailey, Dunlosky & Kane, 2008). Een aanwijzing voor de eerste mogelijkheid werd door Unsworth, Brewer en Spillers (2011) beschreven. Zij lieten proefpersonen lijsten van woorden herinneren die tijdens het encoderen met een rijm of een semantische cue werden gepresenteerd. Wanneer de cue tijdens de encodering en de test hetzelfde was bleken individuen met een hoog WG veel beter dan individuen met een laag WG. Maar wanneer ze niet hetzelfde waren (e.g. met rijm geleerd, met semantische cue getest) presteerden beide groepen even goed (zie ook Delaney & Sahakyan, 2007). De tweede mogelijkheid, met betrekking tot integratie, zou kunnen verklaren waarom in onze studie oefenen onder omstandigheden van sterke competitie alleen voordelig was voor individuen met een hoog WG. Door integratie was het waarschijnlijk mogelijk om de beoefende woorden als cue te gebruiken voor de gerelateerde woorden. Aangezien individuen met een hoog WG een aantal verschillende strategieën gebruiken (repetitie, beeldspraak, groepering, enz.) als zij lijsten van woorden leren (Bailey et al., 2008) is het waarschijnlijk dat beter gebruik van specifieke cues (Unsworth & Engle, 2007b) en het strategische encoderen bijdraagt aan hun sterke prestatie. Samengevat, de vaardigheid om gefocust in het geheugen te zoeken is verbonden met een hoog WG en kan worden verklaard door een superieure opslagcapaciteit.

5.4 Algemene Discussie

De bevindingen in de hoofdstukken 2-4 hebben, zoals eerder besproken, geleid tot de volgende conclusies. WG kan het beste worden omschreven als een domein-algemene bron met enige afhankelijkheid van domein-specifieke subsystemen. Hiermee benadrukken onze bevindingen het belang van de opslagcapaciteit en gefocust zoeken in WG verschillen. In de context van individuele verschillen in WG blijkt dat de vaardigheid om aandachtscontrole uit te kunnen oefenen ook kan worden verklaard door opslagcapaciteit verschillend aan te nemen. Verschillen in opslagcapaciteit beïnvloeden prestaties op twee manieren. Ten eerste kan meer opslagcapaciteit helpen om het doel van een taak en stimulus-reactie verbanden te herinneren. Ten tweede kan de opslagcapaciteit het oproep proces steunen door de mogelijkheid te leveren context specifieke cues te genereren en geavanceerde encoderings strategieën toe te passen. Beide aspecten zijn belangrijk bij het uitvoeren van complexe handelingen, wat ook de de sterke relatie tussen WG en complexe cognitieve vaardigheden verklaart (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Daneman & Carpenter, 1980; Jarrold & Towse, 2006).

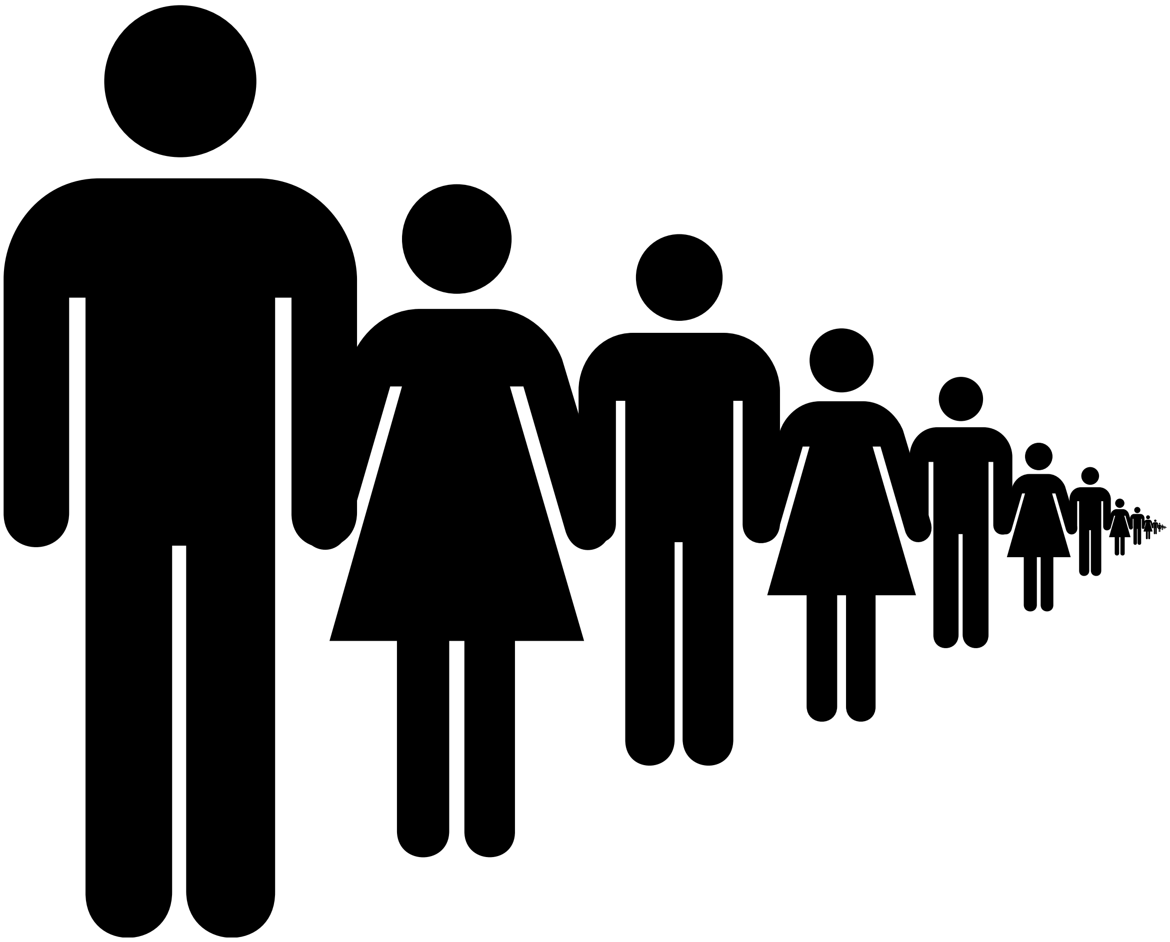
De zogenoemde "embedded" WG modellen van geheugen en aandacht (Cowan, 1995, 2005; Oberauer, 2002, 2006) kunnen dergelijke bevindingen gedeeltelijk verklaren. Deze modellen stellen dat WG een deel uitmaakt van het lange termijn geheugen, dat gekenmerkt wordt door een sterke activatie. Geheugensporen of taak doelen kunnen door deze activering worden vertegenwoordigd. Individuele verschillen in WG worden bepaald door de hoeveelheid van objecten die bijgehouden kunnen worden in de focus van de aandacht of de levensduur van hun activering (Cowan, 2005). Als alternatief zou de domein-algemene episodische buffer, de meest recente toevoeging aan Baddeley's werkgeheugen model, hetzelfde doel dienen (Baddeley, 2000, 2001). Het belangrijkste verschil tussen de bovengenoemde WG modellen en de aandachtscontrole hypothese (Engle et al., 1999) is hun nadruk op de onderliggende reden voor capaciteitsgrenzen. Terwijl de sterke interpretatie van de aandachtscontrole hypothese suggereert dat lage WG individuen zonder opzet irrelevante informatie encoderen (Awh & Vogel, 2008), wat leidt tot een kleinere gemeten capaciteit voor relevante informatie, vonden we in hoofdstuk 3 dat het vermogen om irrelevante informatie te negeren voor iedereen aanwezig was ongeacht onderlinge WG verschillen. Dergelijk "goed nieuws" voor individuen met een laag WG kan desalniettemin afhankelijk zijn van de specifieke taak contexten die hun vermogen om de taak doel bij te houden niet overbelasten (Hutchison, 2011; Kane & Engle, 2003;. Morey et al., 2012). Toch moet de asymmetrie van het oproepen uit het korte termijn geheugen van serielë informatie (hoofdstuk 2) en de randvoorwaarden voor visuele selectieve aandacht (hoofdstuk 3) nog in WG modellen worden opgenomen (zie ook de discussie van hoofdstuk 2 en 3 voor details).

Toekomstige studies zouden deze kwesties moeten behandelen. Bijvoorbeeld door te testen of de asymmetrie in seriële oproepen (hoofdstuk 2), kan voortkomen uit een levenslange oefening met verbale informatie (Logie, Cocchini, Delia Sala, & Baddeley, 2004). Dit kan worden bereikt door het voorleggen van verschillende versies van onze duale taken aan dove of zeer jonge personen. Of een dergelijke aanpak zal leiden tot een alomvattend begrip van geheugen, bijvoorbeeld binnen een perceptuele-gebaren kader (Hughes, Marsh, & Jones, 2009), is onbekend. In het licht van onze bevindingen lijkt een compromis tussen de modellen gericht op domein-specificiteit of domein-algemeenheid onvermijdelijk. Ook is er meer onderzoek nodig om duidelijke randvoorwaarden te formuleren voor visueel selectieve aandacht, zoals besproken in hoofdstuk 3. Hoewel afleiding alleen invloed op individuen met een laag WG heeft als deze opvallend en onverwacht is (Fukuda & Vogel, 2009; Sörqvist, 2010), kunnen bepaalde afleidingen ook fungeren als een herinnering van het taak doel. Bovendien lijkt het mogelijk dat de afleiders altijd geëncodeerd worden als de perceptuele belasting laag, of het WG hoog is (Forster & Lavie, 2011; Lavie, Hirst, de Fockert, & Viding, 2004). Rekening houden met deze factoren en het uit elkaar houden van hun respectievelijke invloed in toekomstige studies is essentieel. Ten slotte kan een beter begrip van de relatie tussen WG en oproep specificiteit directe praktische implicaties hebben. Sinds gefocust zoeken via het gebruik van specifieke ophaal cues de weerstand tegen interferentie en het effect van oefenen verbeterde, zou de volgende stap moeten zijn om deze bevindingen in een leeromgeving te repliceren. Zo kunnen leraren bijvoorbeeld waarborgen dat tijdens het leerproces zo min mogelijk niet-gerelateerde feiten worden gepresenteerd. Toekomstig onderzoek kan verschillende benaderingen van leren in blokken vergelijken en proberen strategieën aan te leren die het gebruik van contextuele cues verhogen. De inzichten verkregen door een soortgelijke aanpak zal hopelijk leiden tot een betere leeromgeving voor alle mensen ongeacht de grote van hun WG.

De praktische lessen uit onze bevindingen zijn talrijk. Het blijkt dat WG geen beperkende factor voor het leren hoeft te zijn. Onder de juiste omstandigheden kunnen mensen met een lage en hoge capaciteit op een vergelijkbaar niveau presteren. Toch zullen individuen met een lage capaciteit bijzonder profiteren van omgevingen zonder onverwachte afleidingen. Zo zal bijvoorbeeld het aan laten van de tv tijdens het studeren waarschijnlijk een onnodige sterke afleiding vormen. Zoals geïllustreerd door de irrelevante geluidseffecten (Beaman, 2004), zou men individuen met een laag WG niet aanraden om naar muziek te luisteren die onregelmatig voorkomende verbale informatie bevat (bv. rap muziek) omdat deze eerder hun aandacht kan vangen, wat wederom kan leiden tot het tijdelijke verlies van de taak doel. Terwijl hoge WG individuen vaak resistenter lijken ten opzichte van afleiders lijken ze niet immuun. Vooral als afleiding intern wordt gecreëerd, bijvoorbeeld door zich zorgen te maken over de uitkomst van een test (Beilock & Carr, 2005). Daarom is het minimaliseren van externe en interne afleiding waarschijnlijk goed voor zowel individuen met een laag als wel individuen met een hoog WG.

Ten slotte moet worden opgemerkt dat de mensen misschien wel heel goed door hebben dat hun WG beperkt is waardoor ze zullen proberen om dit strategisch te compenseren. Zoals besproken in hoofdstuk 3 leken individuen met een laag WG hun capaciteit voor de meest relevante informatie te bewaren. Het is dus mogelijk dat individuen met een hoog WG juist goed presteren omdat zij gebruik maken van hun extra capaciteit om taakdoelen proactief bij te houden (bijv. Braver, 2012). Echter kunnen lage WG personen worden geïnstrueerd om effectieve encodering strategieën te volgen. Bijvoorbeeld: wanneer individuen met een laag WG geïnstrueerd werd om woorden die ze moesten leren in een verhaal te integreren, presteerden zij even goed als individuen met een hoog WG (Cokely, Kelley , & Gilchrist, 2006). In de samenvatting van hoofdstuk 4 hebben we besproken hoe strategische encodering tot voordelen voor individuen met een hoog WG kan leiden (Bailey et al., 2008). Omdat het strategische encoderen ook een voordeel kan zijn in de taken om WG te meten, door het combineren van letters tot een woord of het creëren van een zinvolle figuur van ruimtelijke locaties, blijft het te bezien hoeveel de neiging om geavanceerde encodering strategieën te hanteren invloed heeft op de relatie tussen WG en andere cognitieve vaardigheden.

Kortom, de studies in dit proefschrift verbeteren ons begrip van de structuur en variabiliteit van het WG. Theoretische modellen moeten mogelijk worden aangepast en nieuwe randvoorwaarden voor de interactie tussen WG en selectieve aandacht moeten worden geïntegreerd. Enkele van de bevindingen kunnen helpen bij het oprichting van effectieve leer- en werkomgevingen die inspelen op de behoeften en mogelijkheden van mensen met een verschillende capaciteit in WG. Als de juiste omstandigheden gecreëerd worden kunnen mensen met verschillende vaardigheden vaak even goed presteren.



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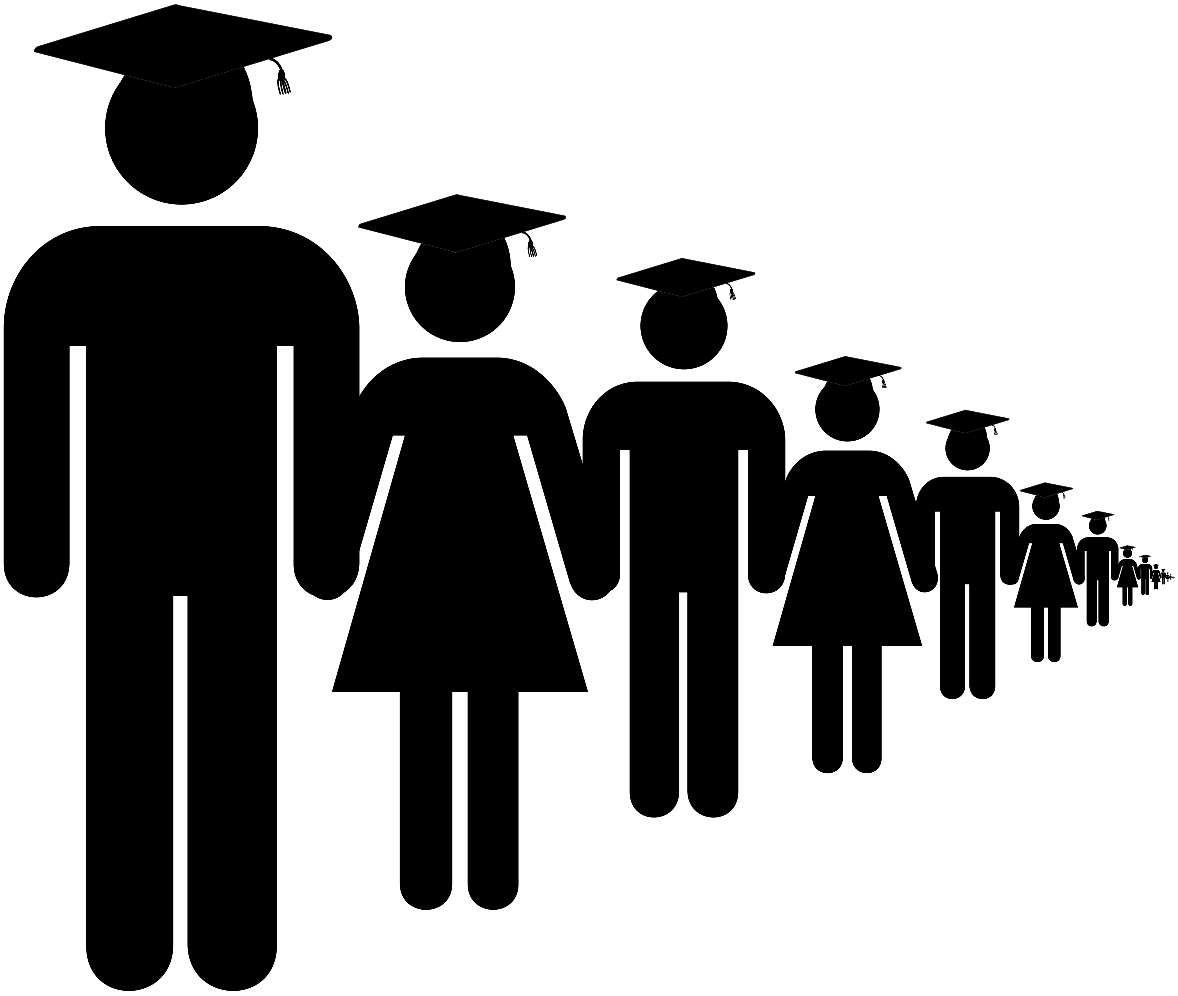

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Working memory capacity (WMC) is the workspace in which we process, retrieve and hold the most relevant information while ignoring distracting stimuli. In this thesis, it is argued that WMC reflects a mainly domain-general resource which represents memory capacity and some attentional control abilities. To support these statements, three empirical chapters are presented. First, simultaneously maintaining stimuli from the verbal and spatial domain in working memory provoked substantial interference compared to maintaining stimuli from only a single domain. Therefore, working memory may be understood as a predominantly domain-general resource (Chapter 2). Second, WMC appeared not to be synonymous with the ability to filter irrelevant information. While individuals with low and high-WMC were equally able to attend relevant information, high-WMC individuals seemed to utilize their bigger memory capacity to encode less relevant information when it could benefit performance (Chapter 3). Third, individuals with high-WMC appeared capable of a more focused memory search. When competition between memory traces during retrieval from long-term memory was strong, low-WMC individuals exhibited patterns of forgetting which suggested that they were searching in a bigger search set (Chapter 4). In conclusion, the studies presented in this thesis emphasize the importance of an individuals' storage capacity and the strategy when trying to remember information.